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CS 561: Data Systems Architectures

class 18

Asymmetry & Concurrency Aware Storage Management

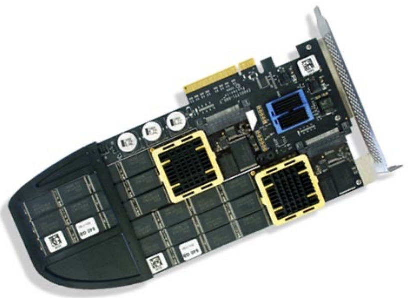
Prof. Manos Athanassoulis

https://bu-disc.github.io/CS561/

Evolution of Storage Hierarchy

HDD

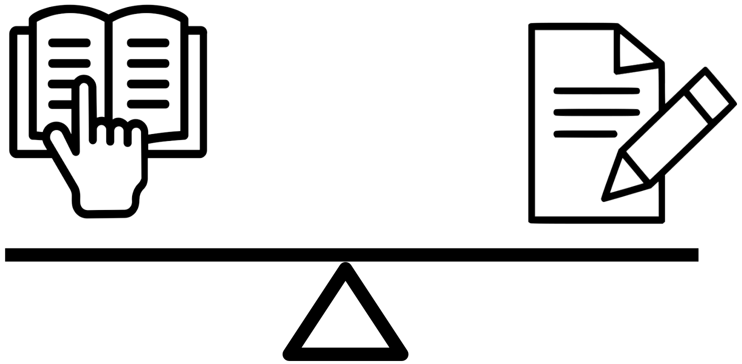
SSD



NVM SSD

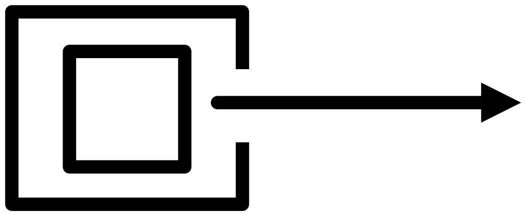
Hard Disk Drives

Hard Disk Drives



Symmetric cost for **Read & Write** to disk

✓



One I/O at a time

✓

Solid-State Drive (SSD)

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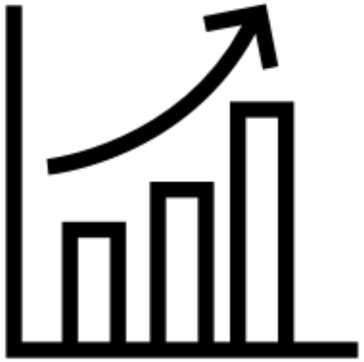
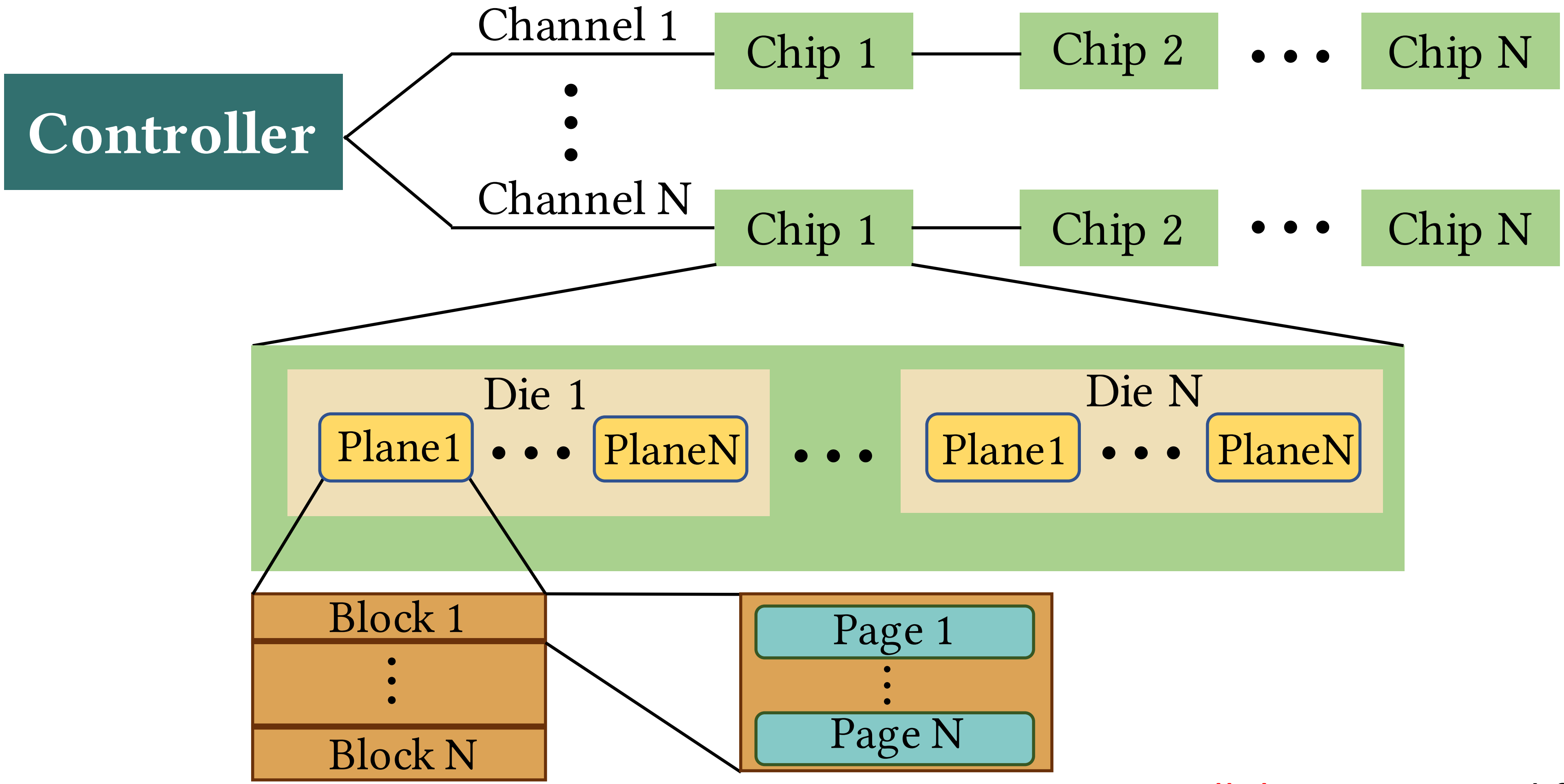
Solid-State Drive (SSD)

No mechanical movement



Fast access, High chip density, Low energy consumption

Internals of an SSD



Parallelism at many different levels (channel, chip, die, plane, block)

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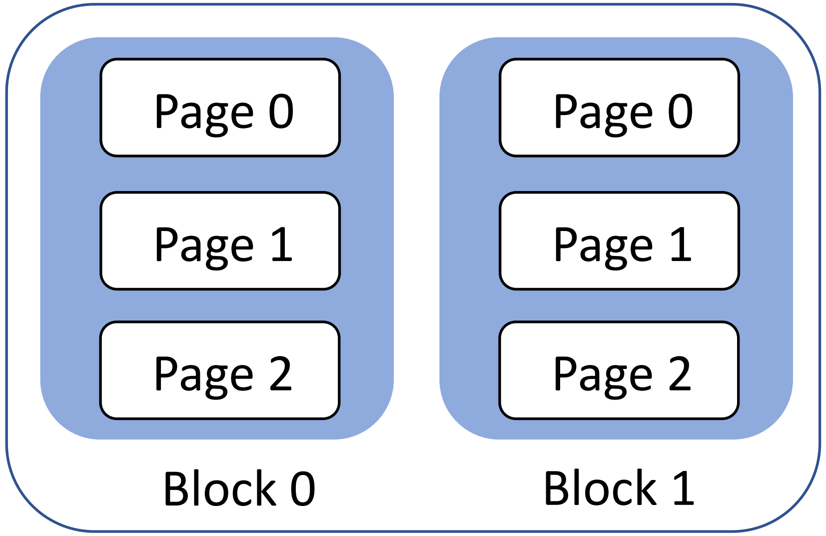
Writes in SSD

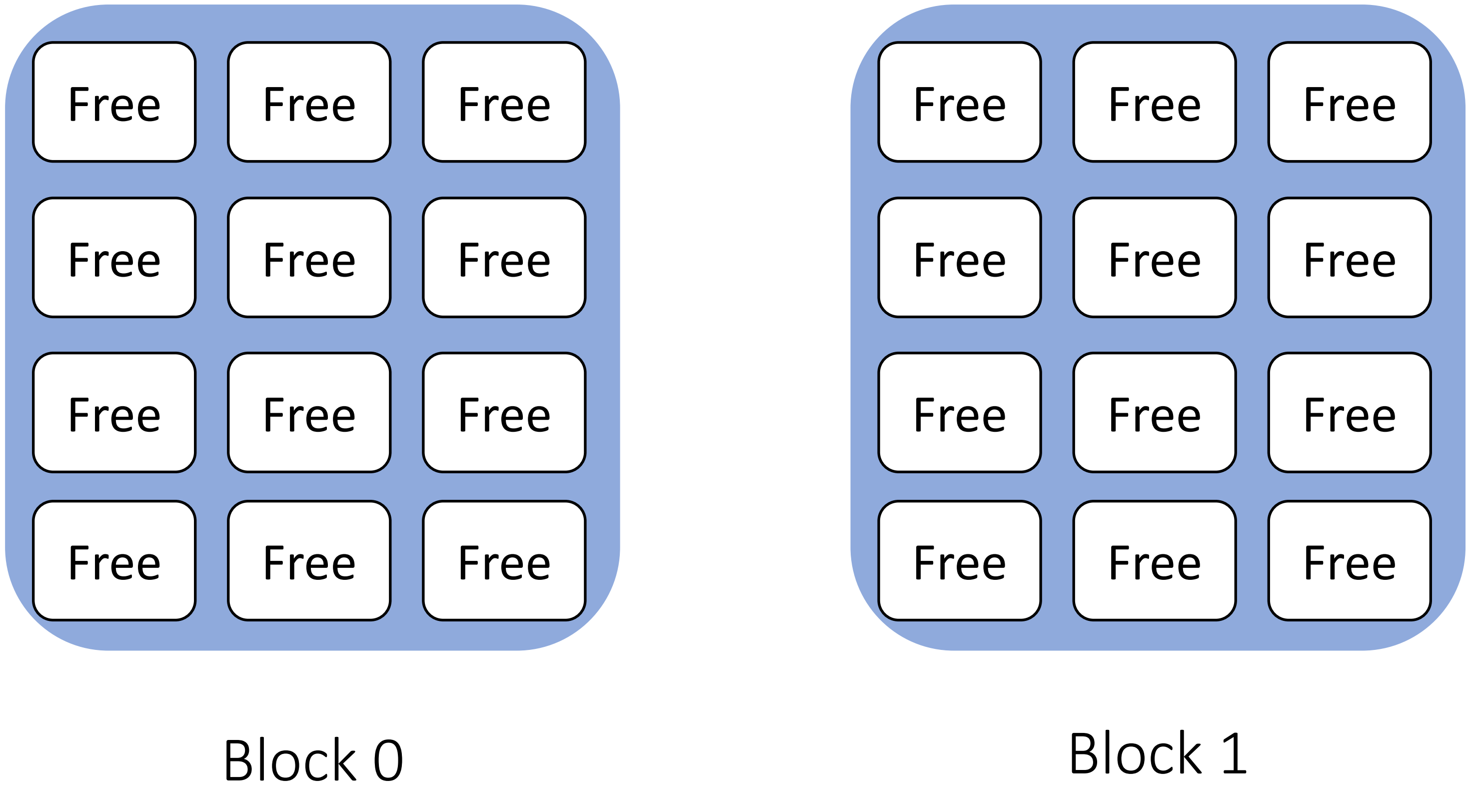
Out-of-place updates cause invalidation

Invalidation causes garbage collection.

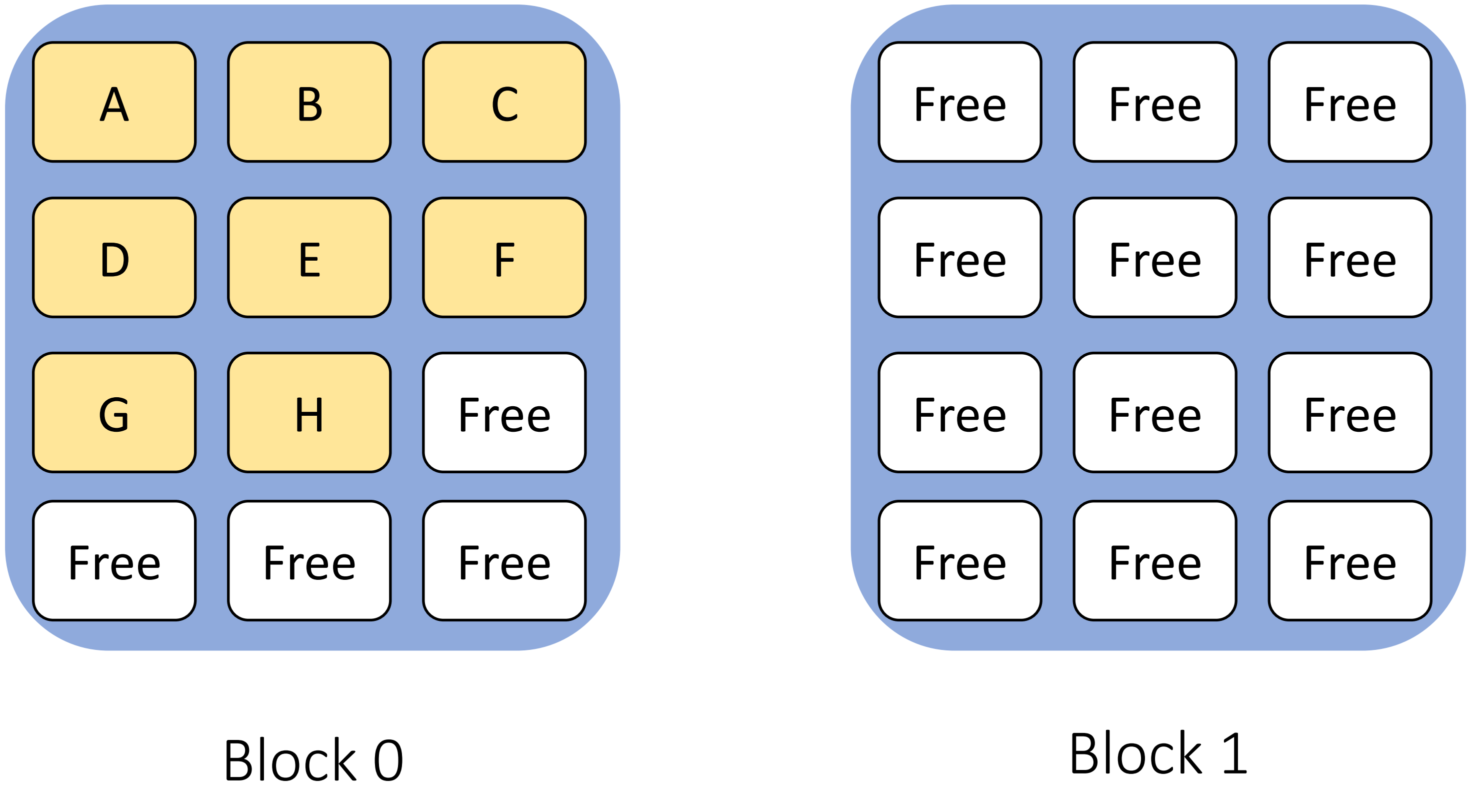


Plane

Writes in SSD



Writes in SSD



Writing in a free page isn't costly!

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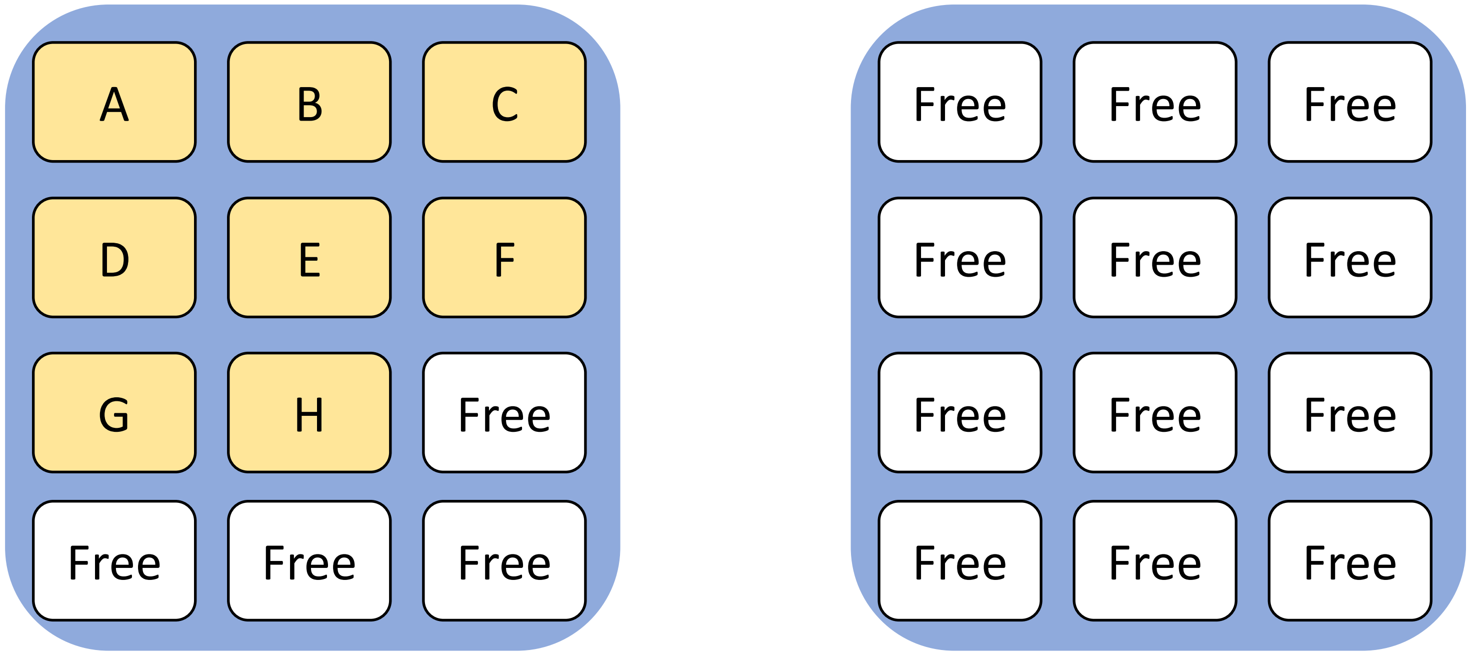
Writes in SSD

Update

A, B, C, D



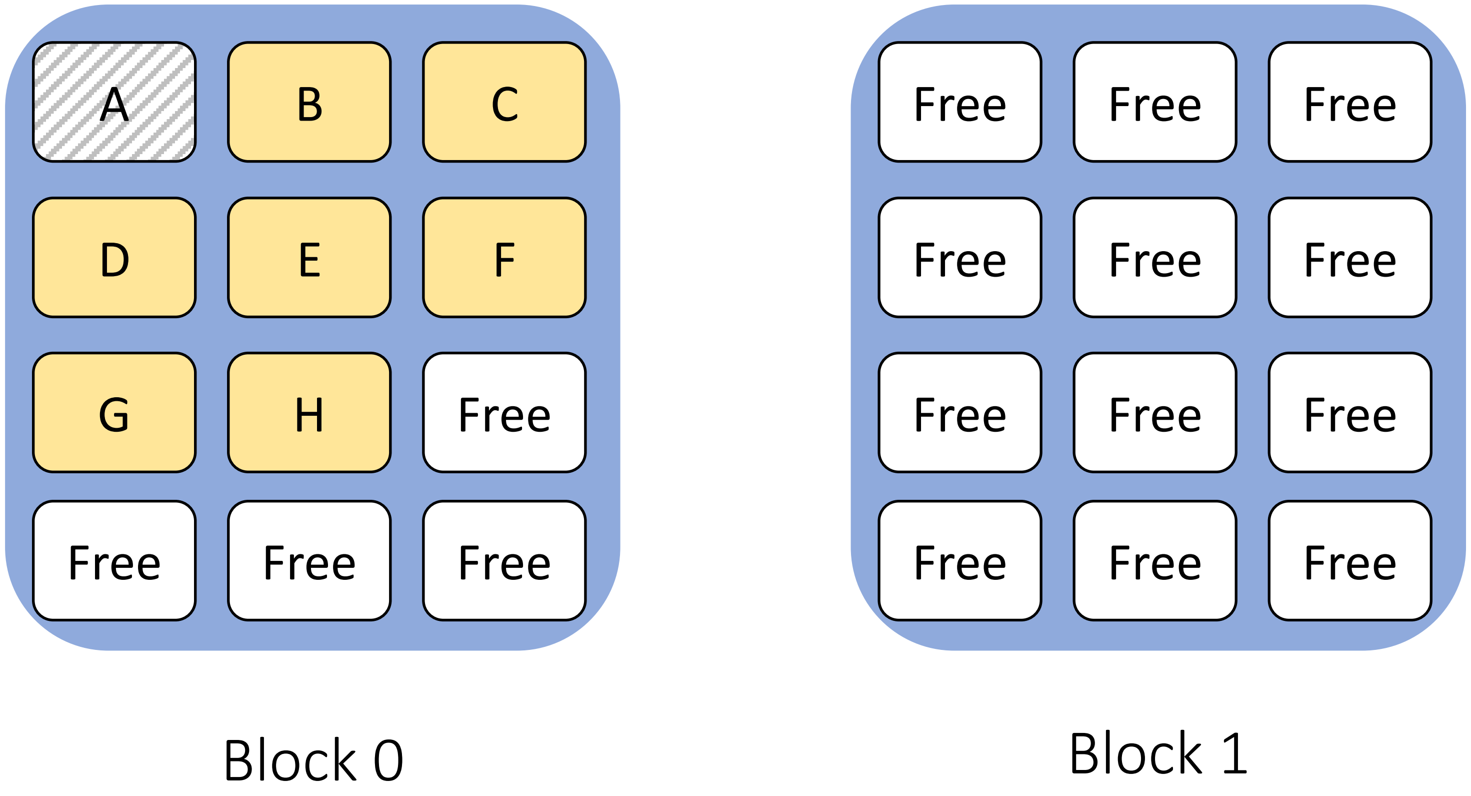
Block 0

Block 1

Writes in SSD

Update

A, B, C, D



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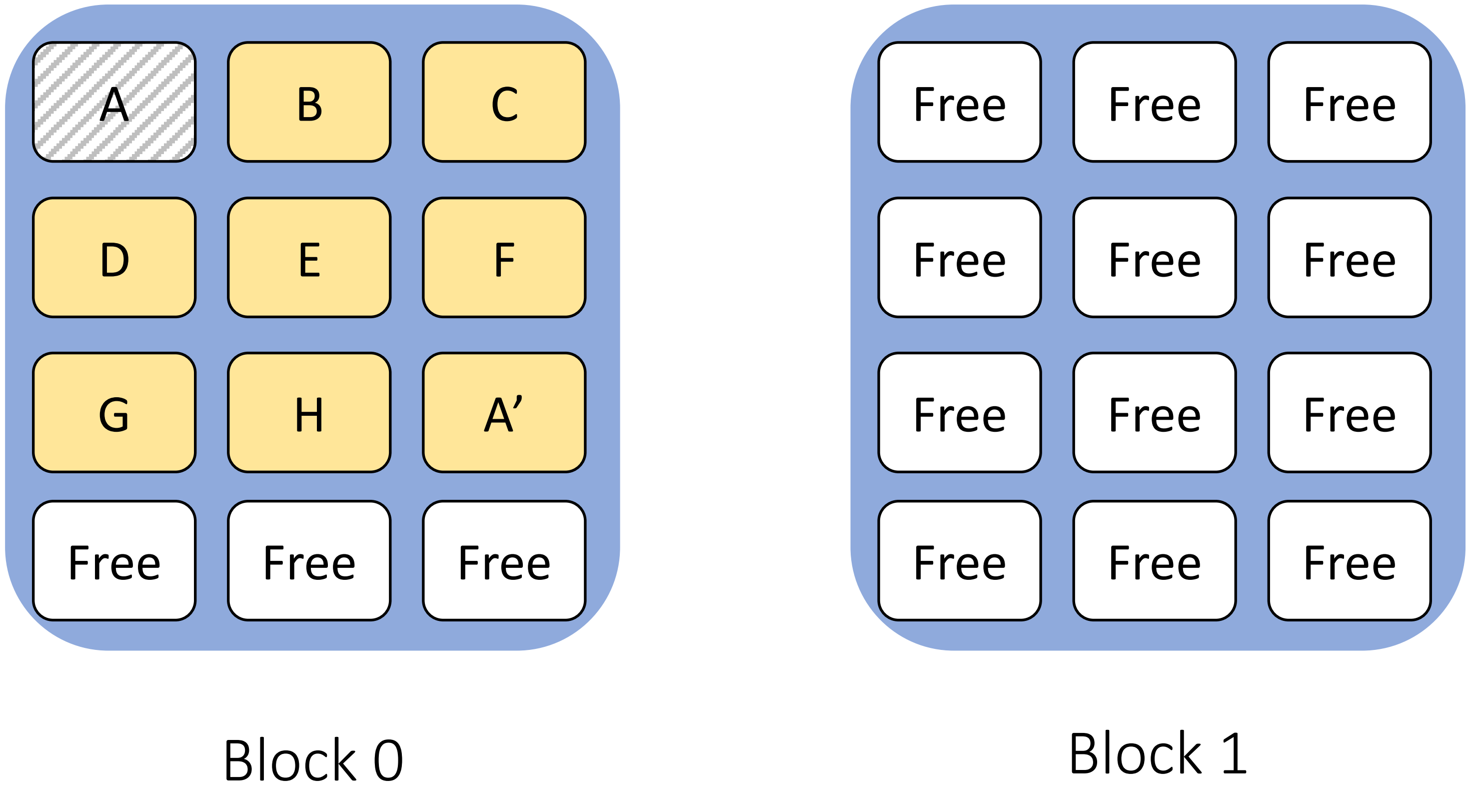
Writes in SSD

Update

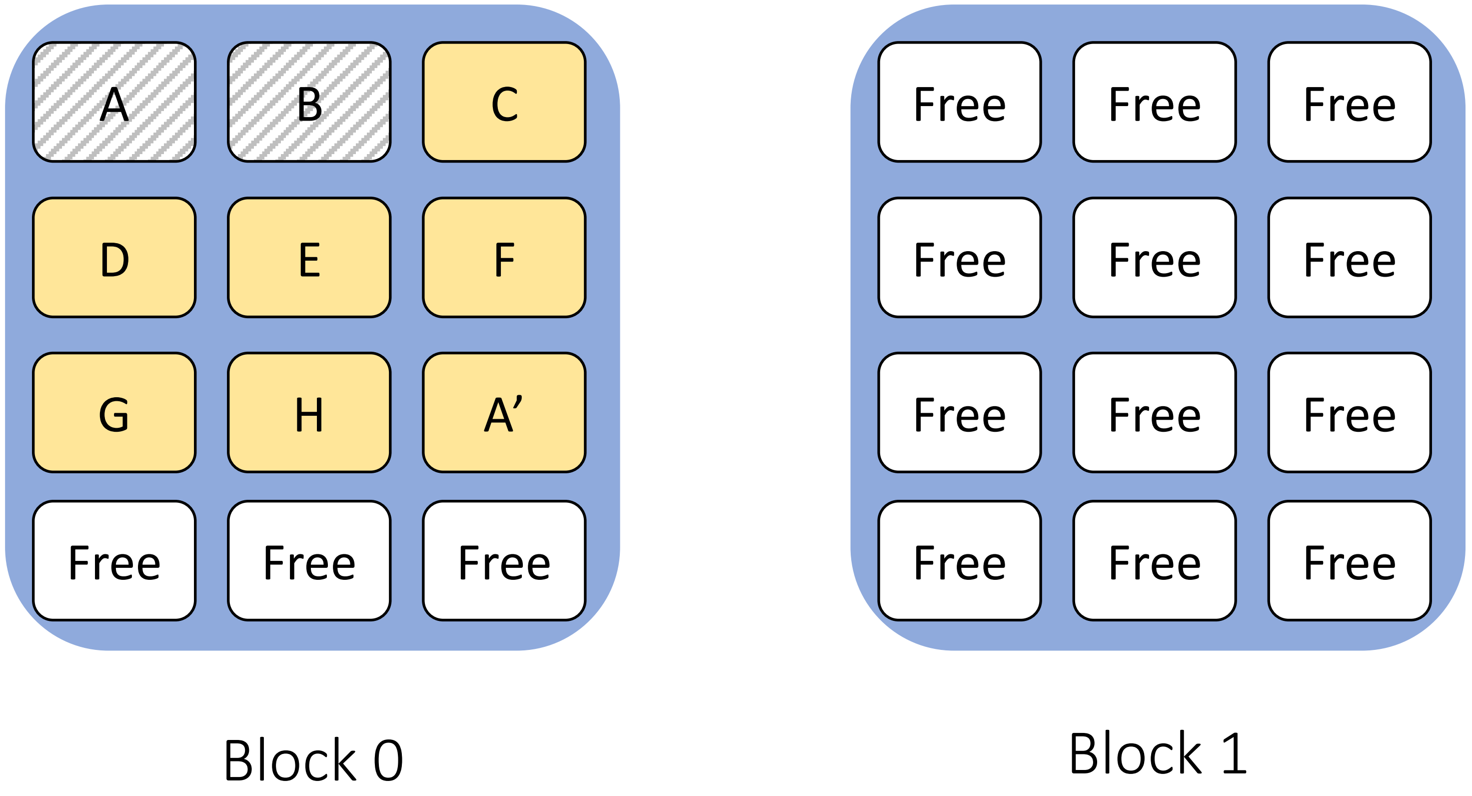
A, B, C, D



Writes in SSD

Update

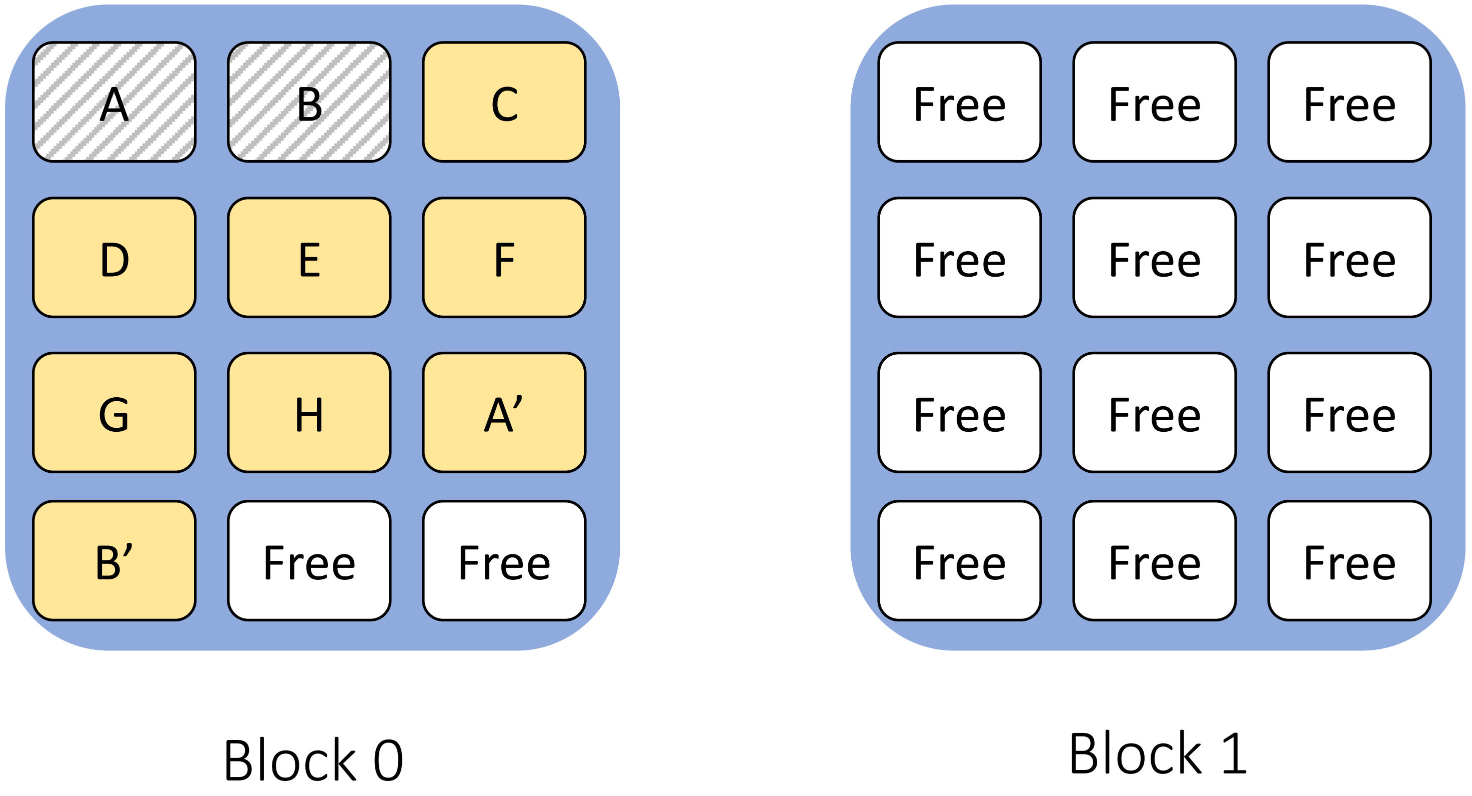
A, **B**, C, D



Writes in SSD

Update

A, **B**, C, D



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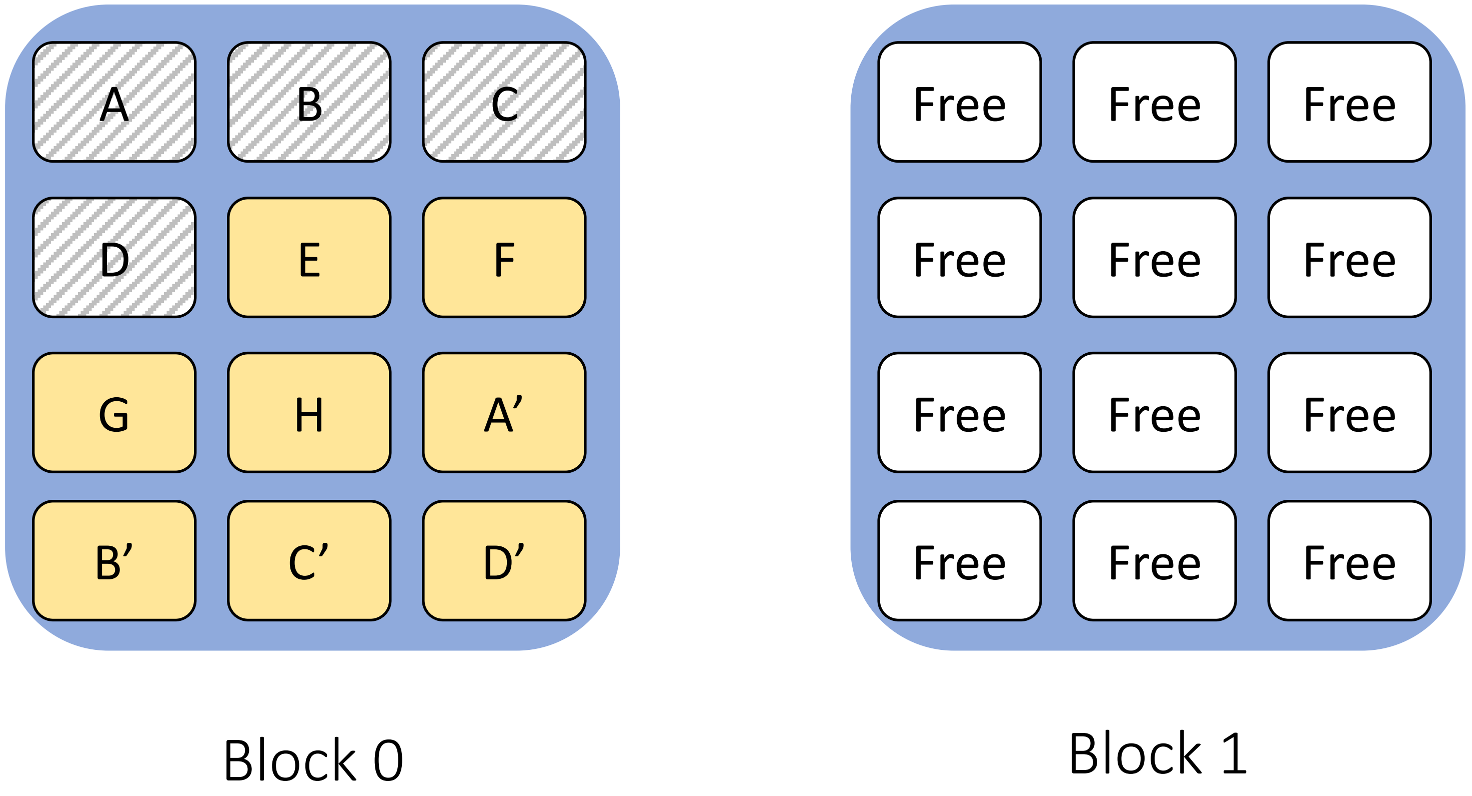
Writes in SSD

Update

A, B, C, D



Not all updates are costly!

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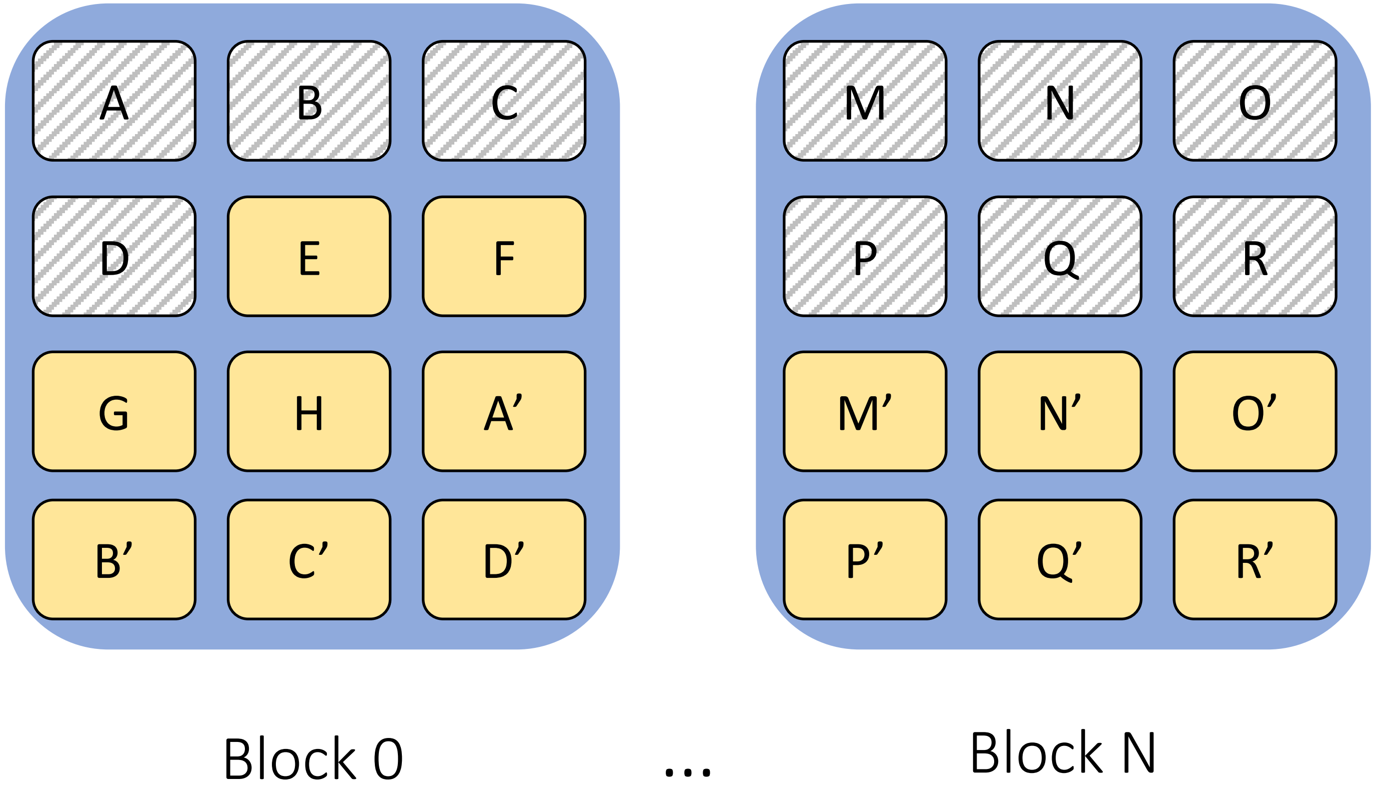
Writes in SSD

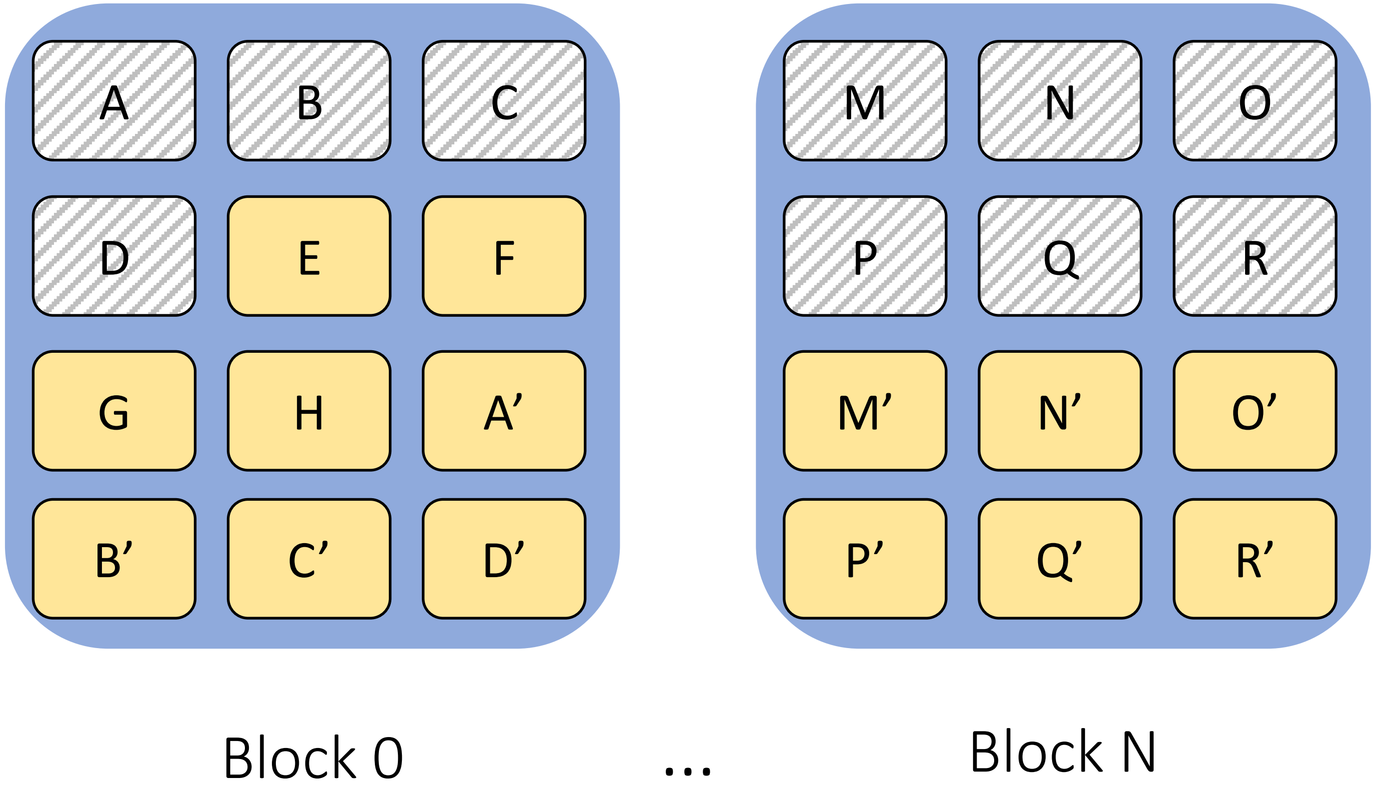
What if there is no space?



Writes in SSD

What if there is no space?

Garbage Collection!



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Writes in SSD

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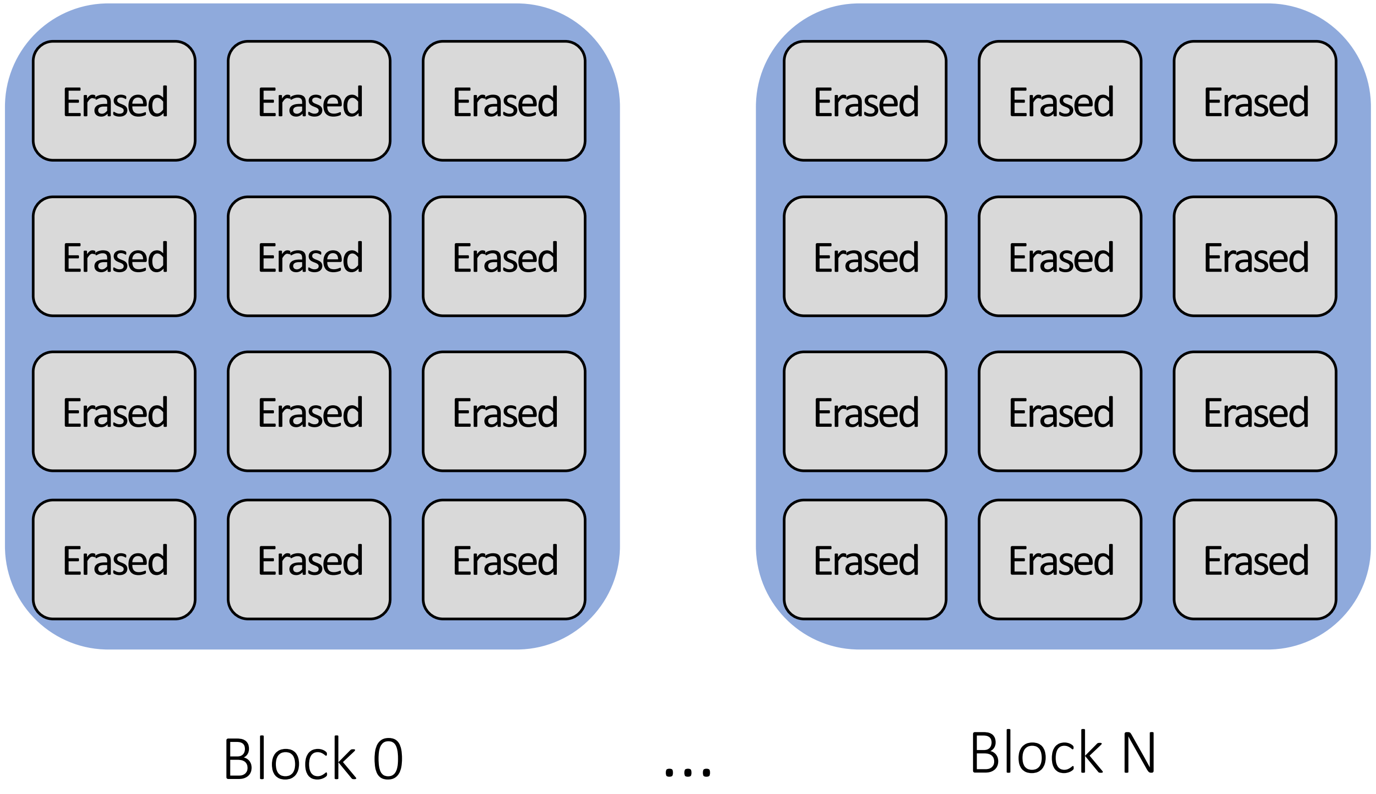

Valid pages:

E	F	G	H	A’	B’	C’	D’	M’	N’	O’	P’	Q’	R’

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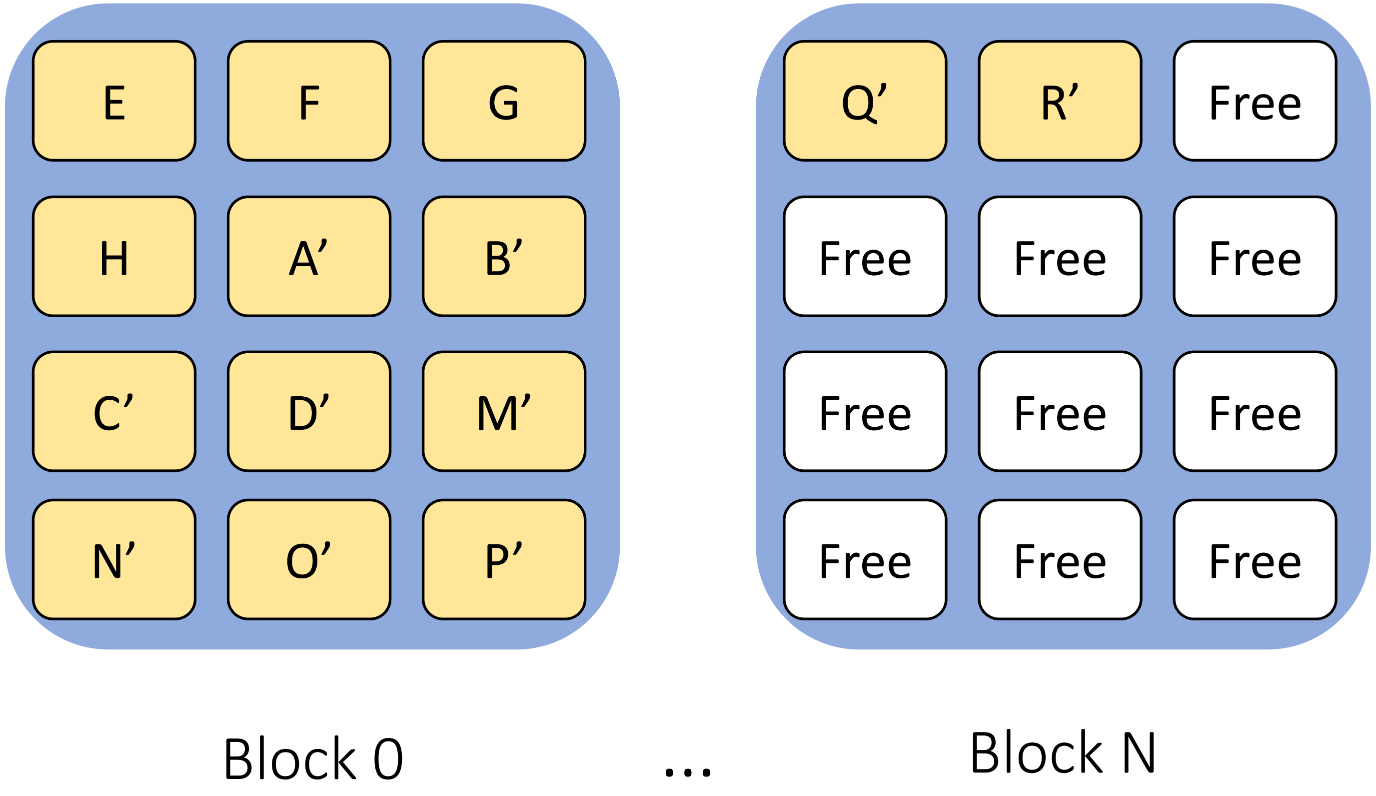
Writes in SSD

What if there is no space?

Garbage Collection!



Writes in SSD

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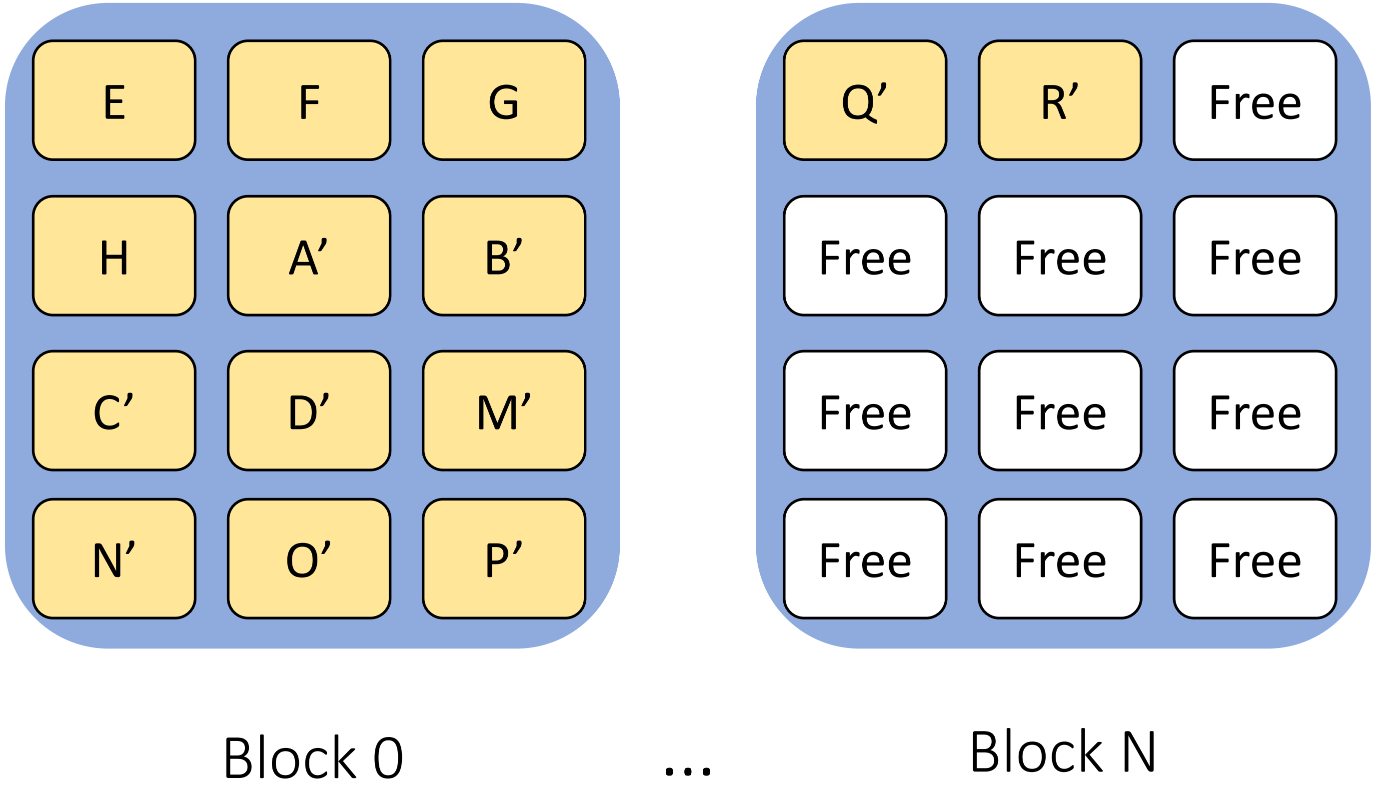
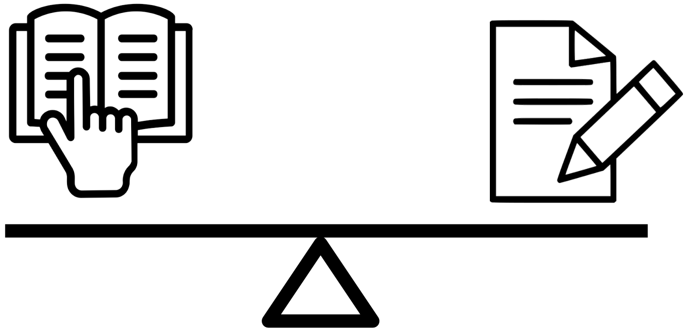


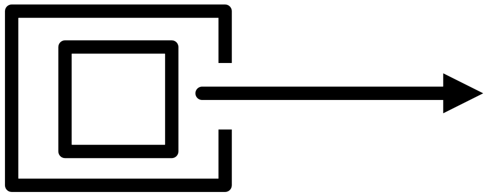
Higher average update cost (due to GC) → ***Read/Write asymmetry***

HDD vs SSD

HDD

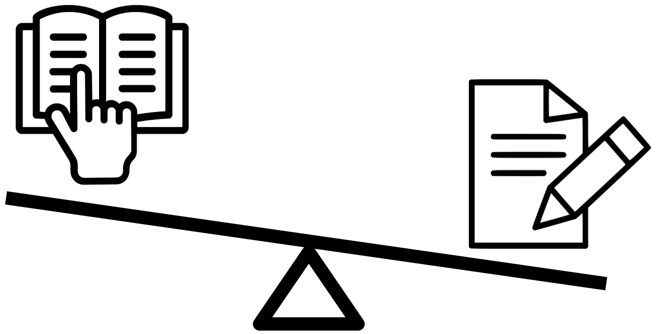


Symmetric cost for Read & Write

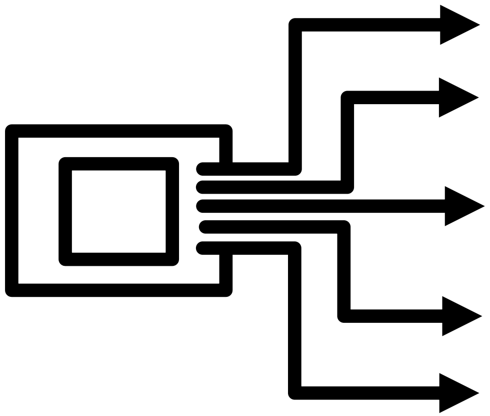


One I/O at a time

SSD



Read/Write Asymmetry



Concurrency

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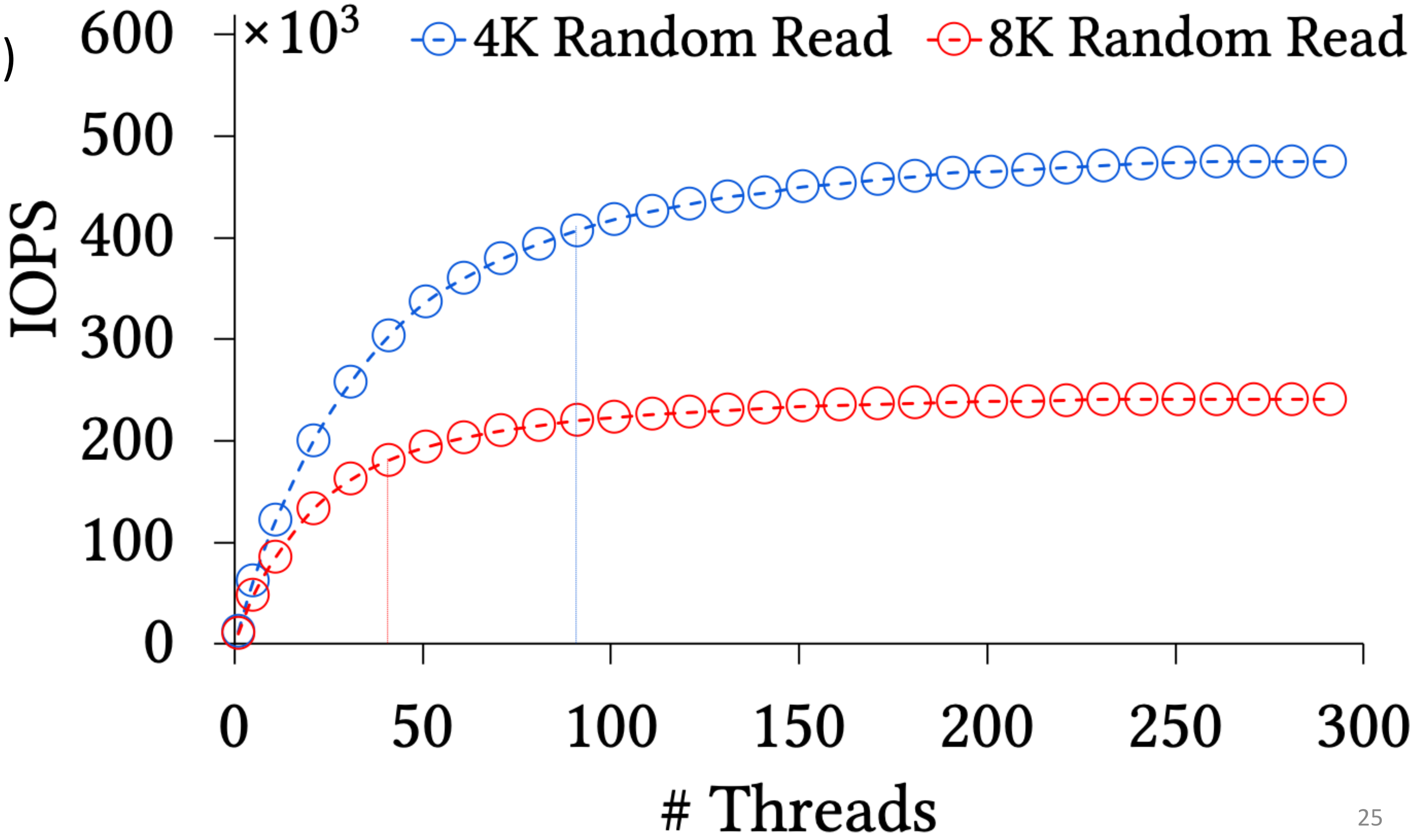
Measuring Asymmetry/Concurrency (With FS)

Device

PCIe SSD - P4510 (1TB)



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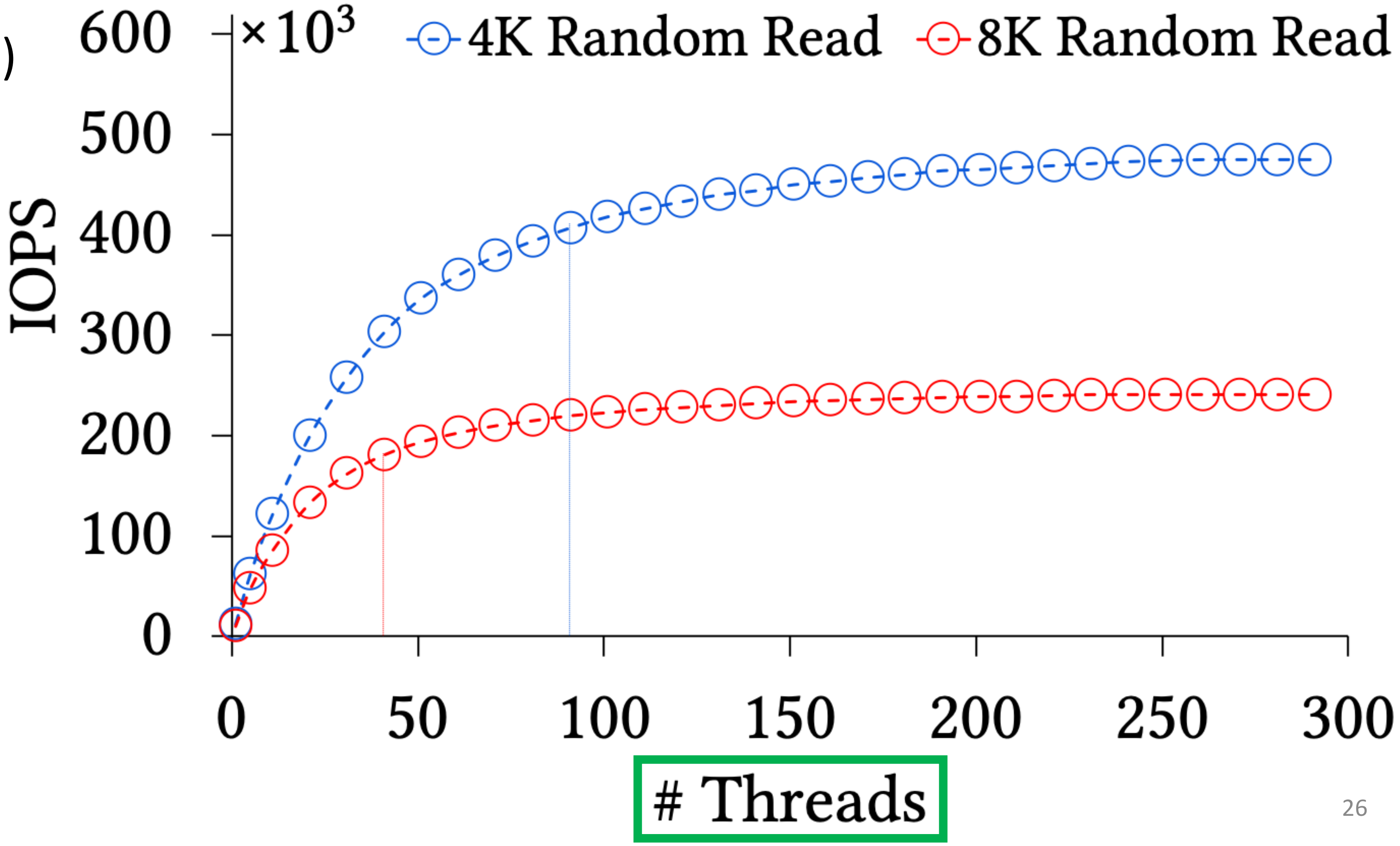

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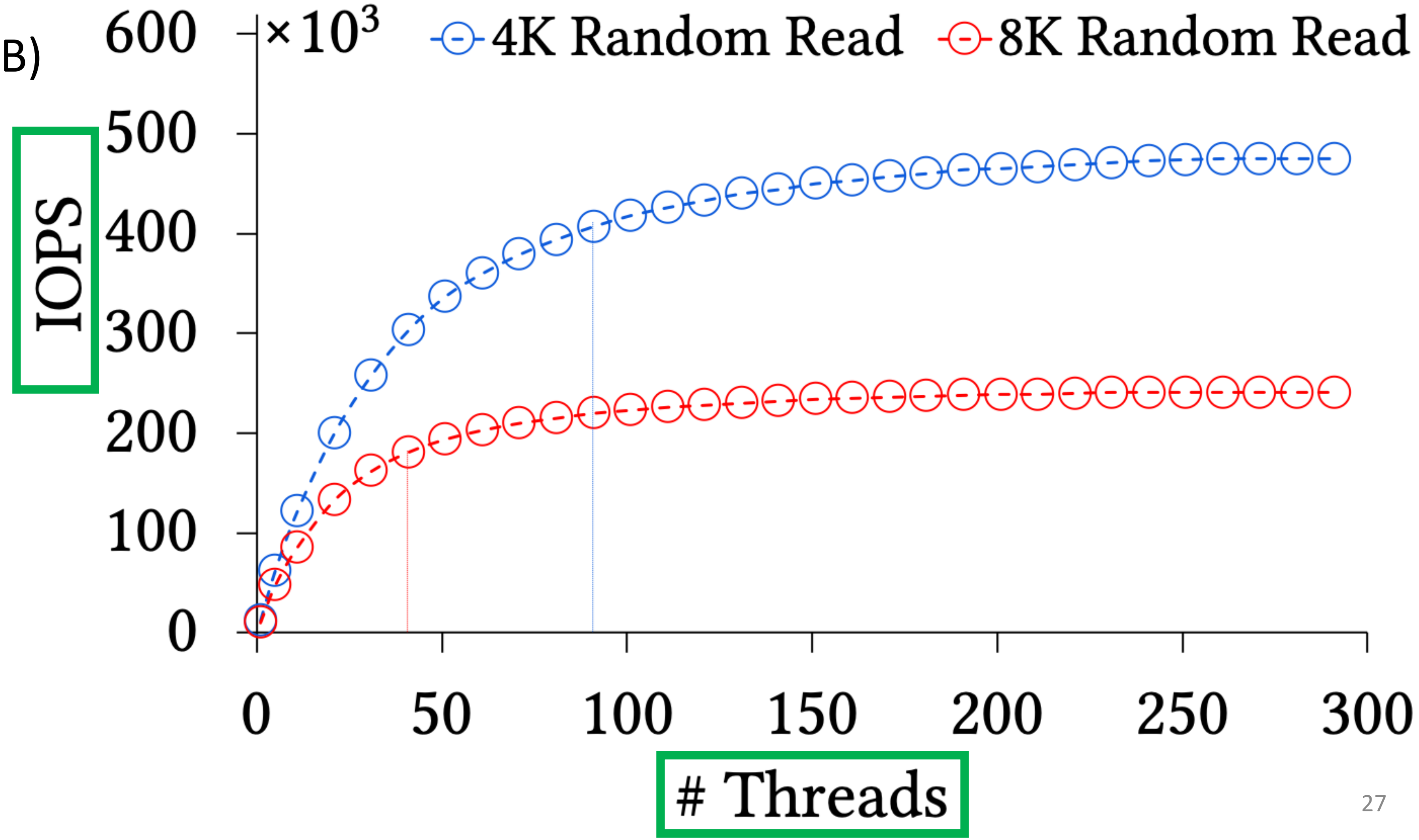

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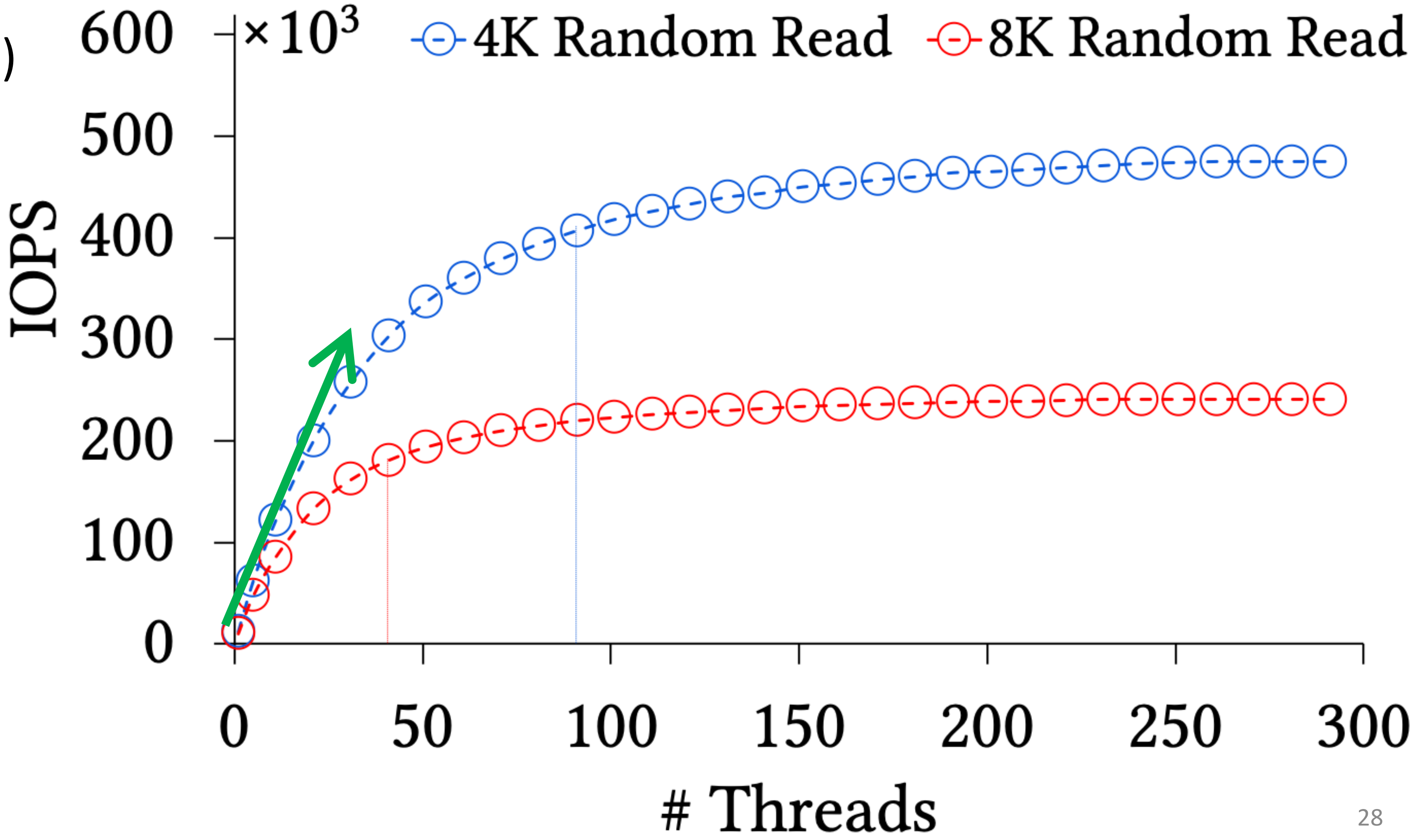

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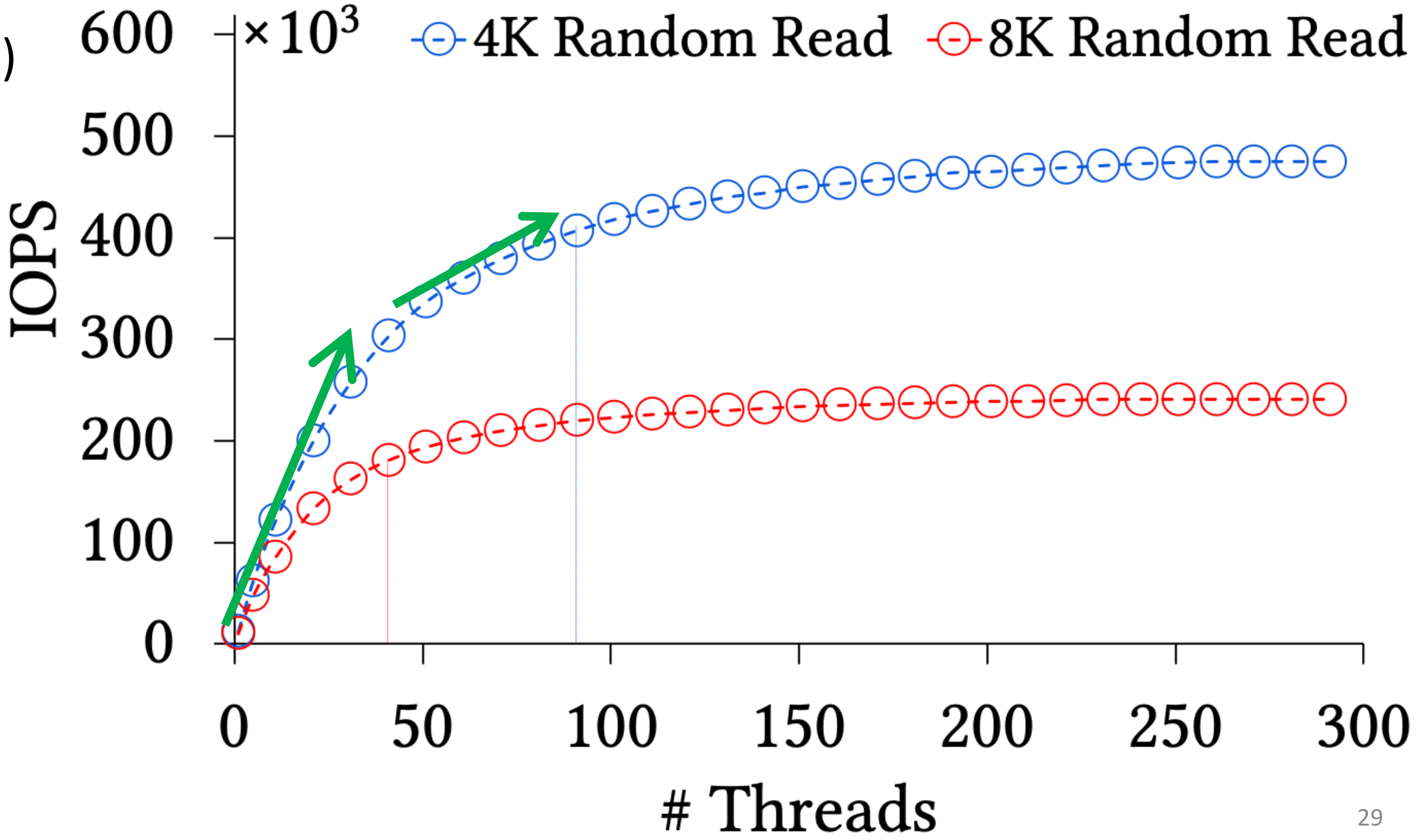

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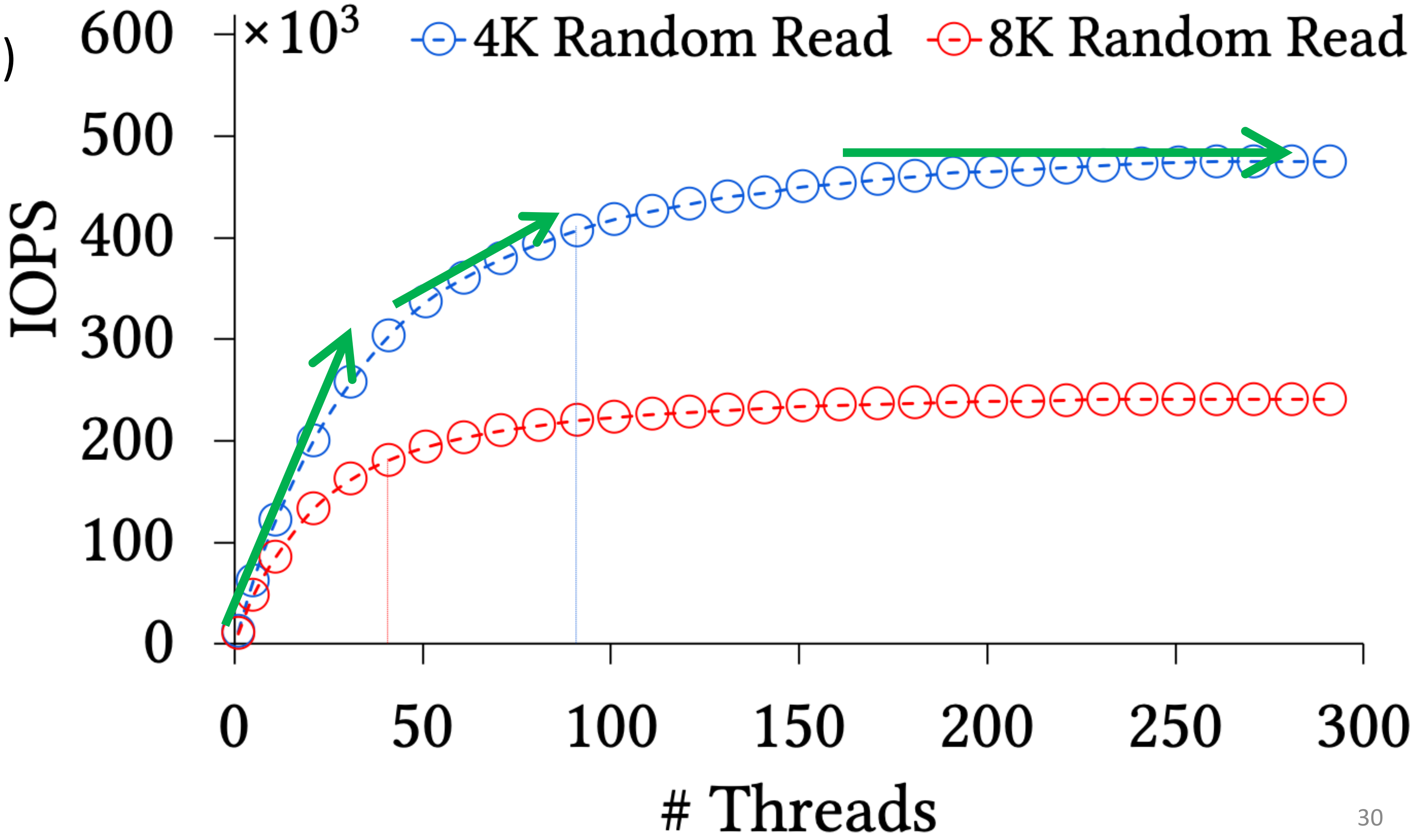

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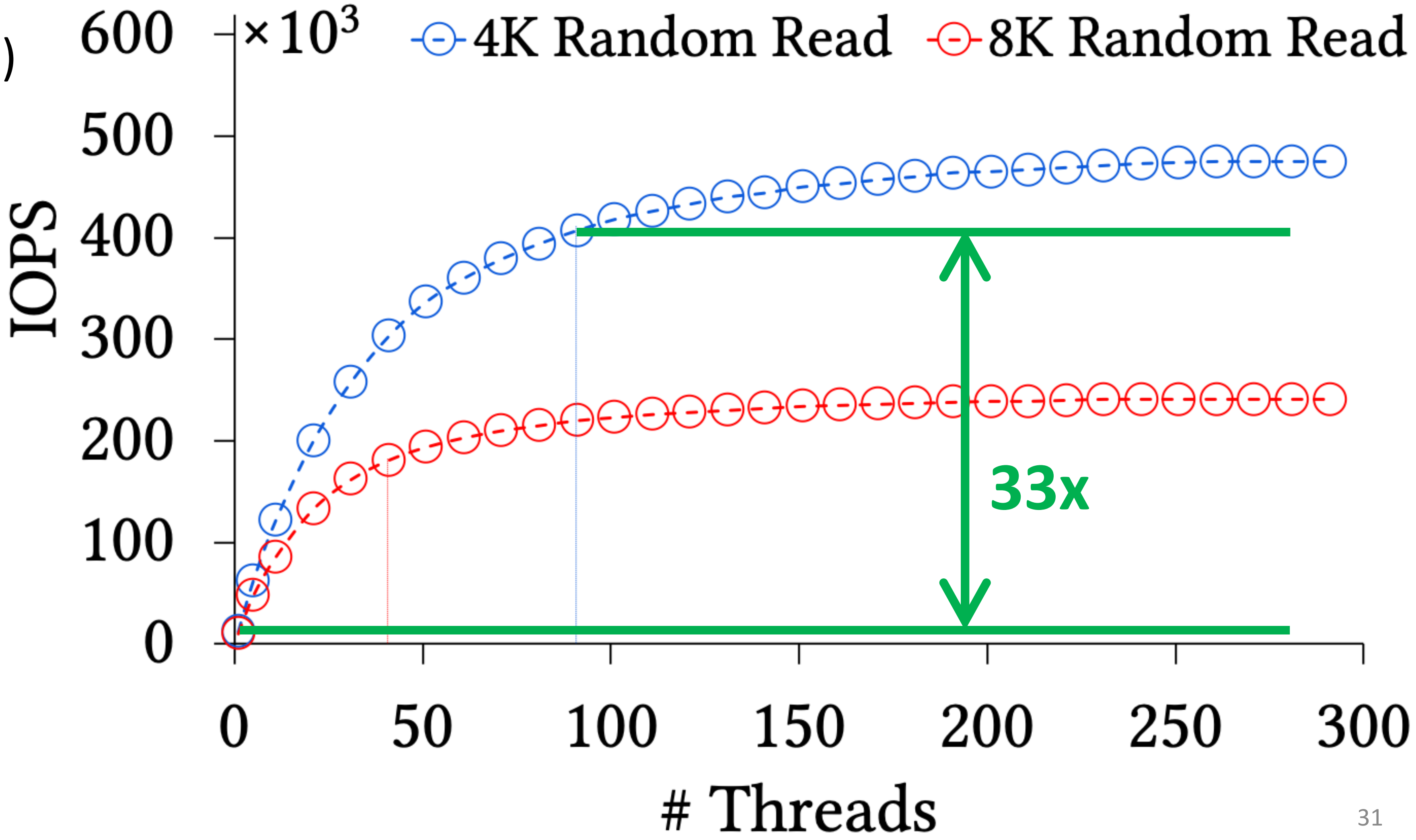

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Measuring Asymmetry/Concurrency (With FS)

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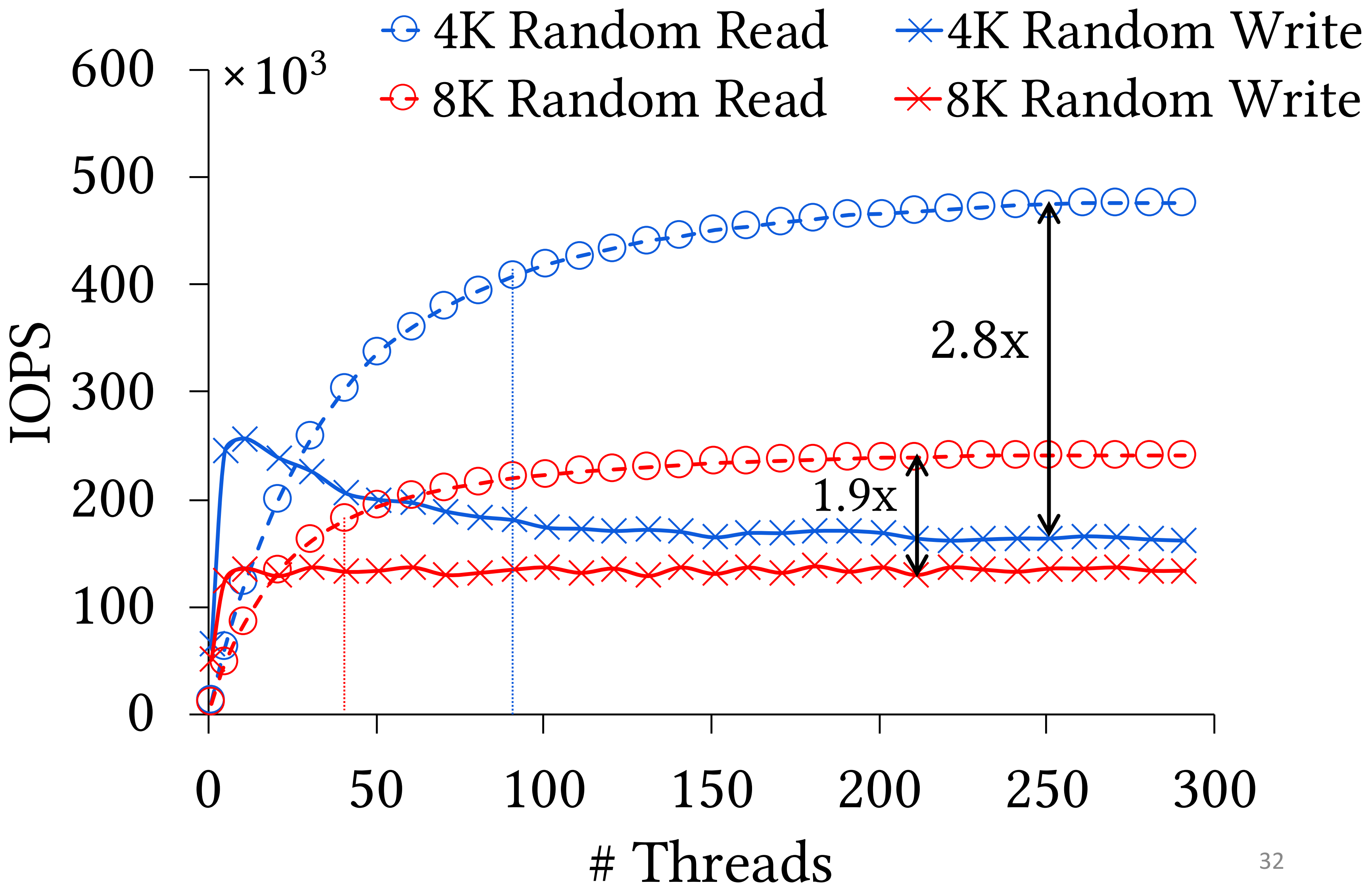

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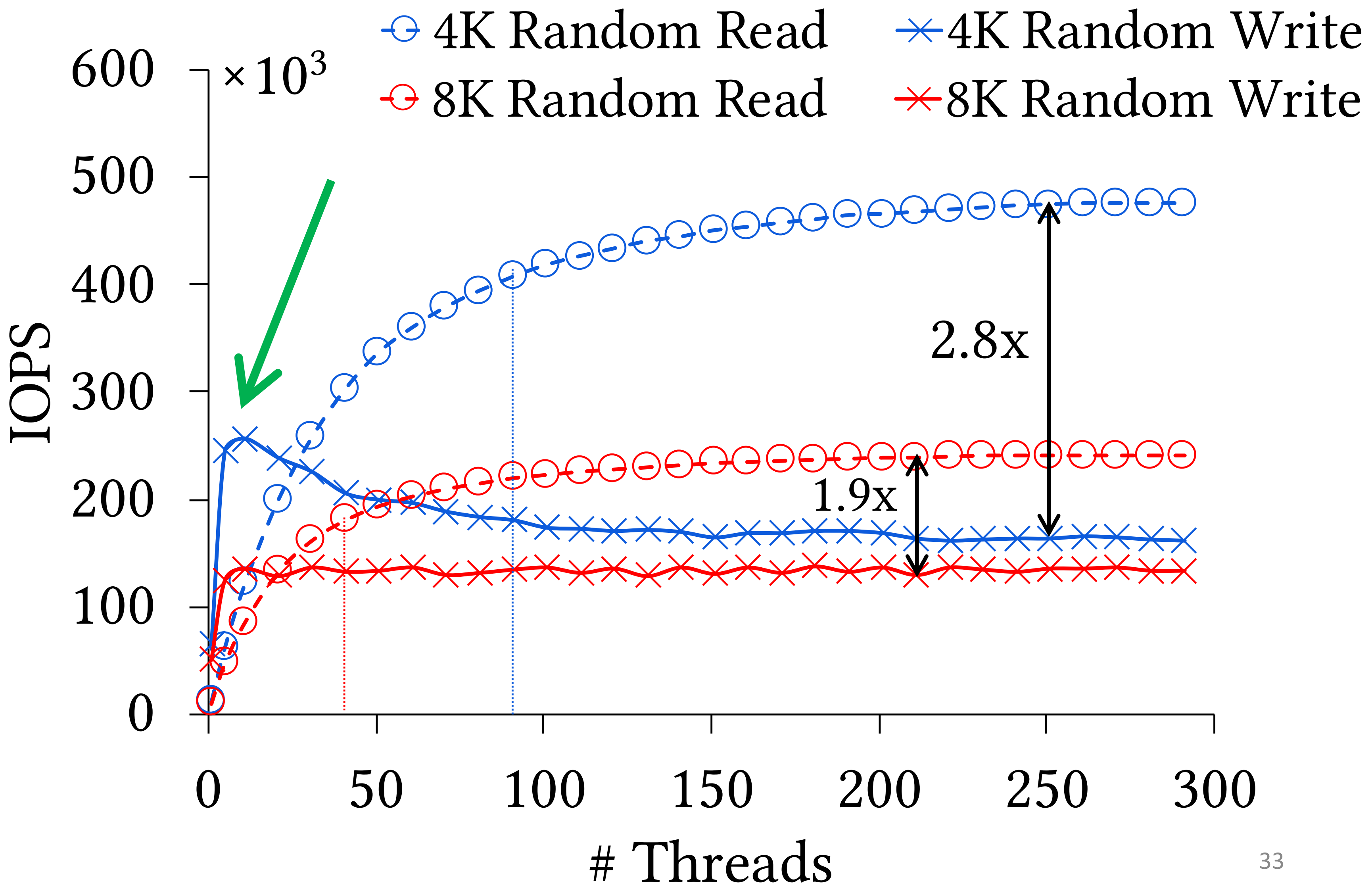

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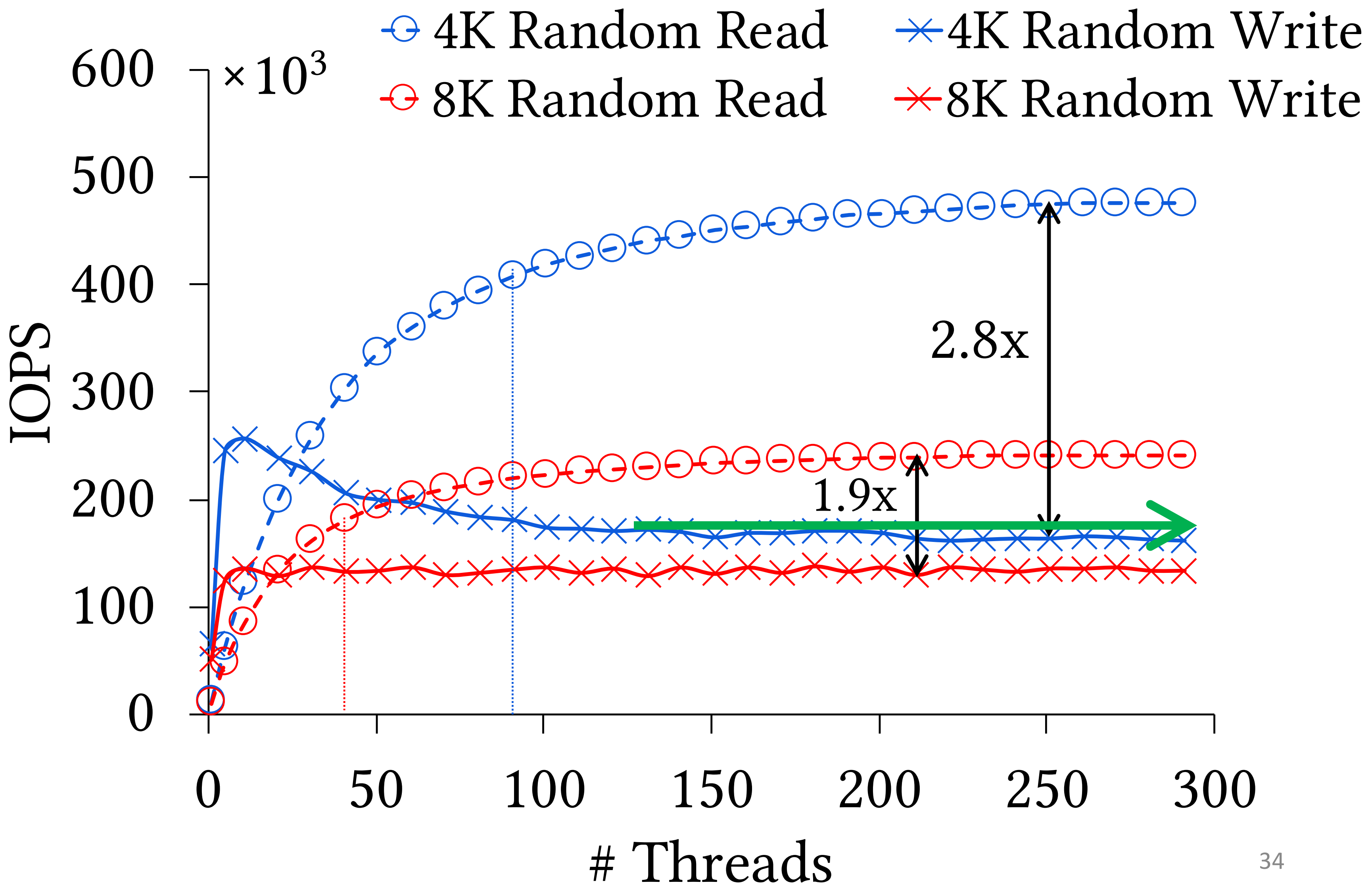

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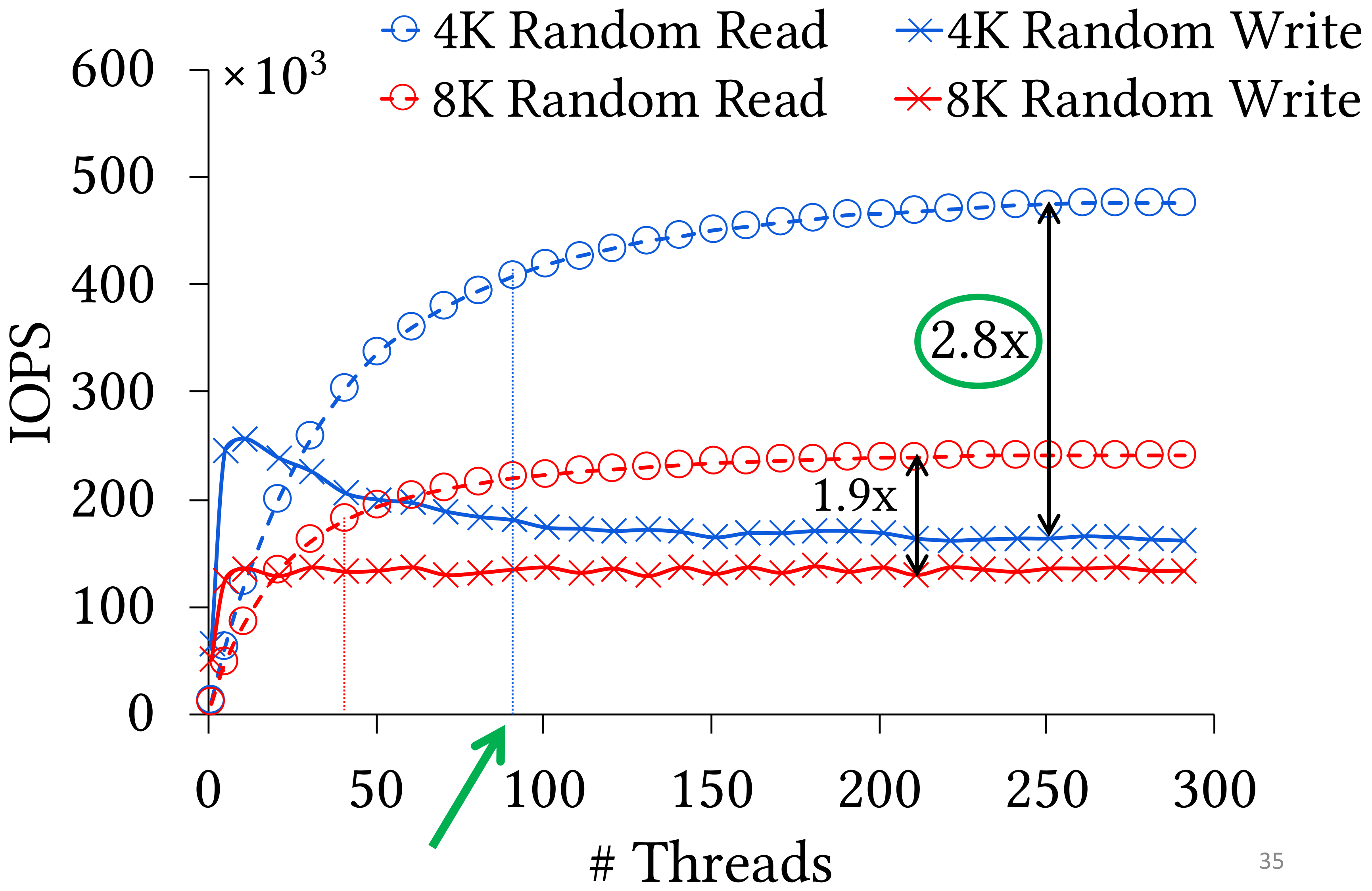
Measuring Asymmetry/Concurrency (With FS)

Device
PCIe SSD - P4510 (1TB)

For 4K random read,

Asymmetry: 2.8

Concurrency: 80



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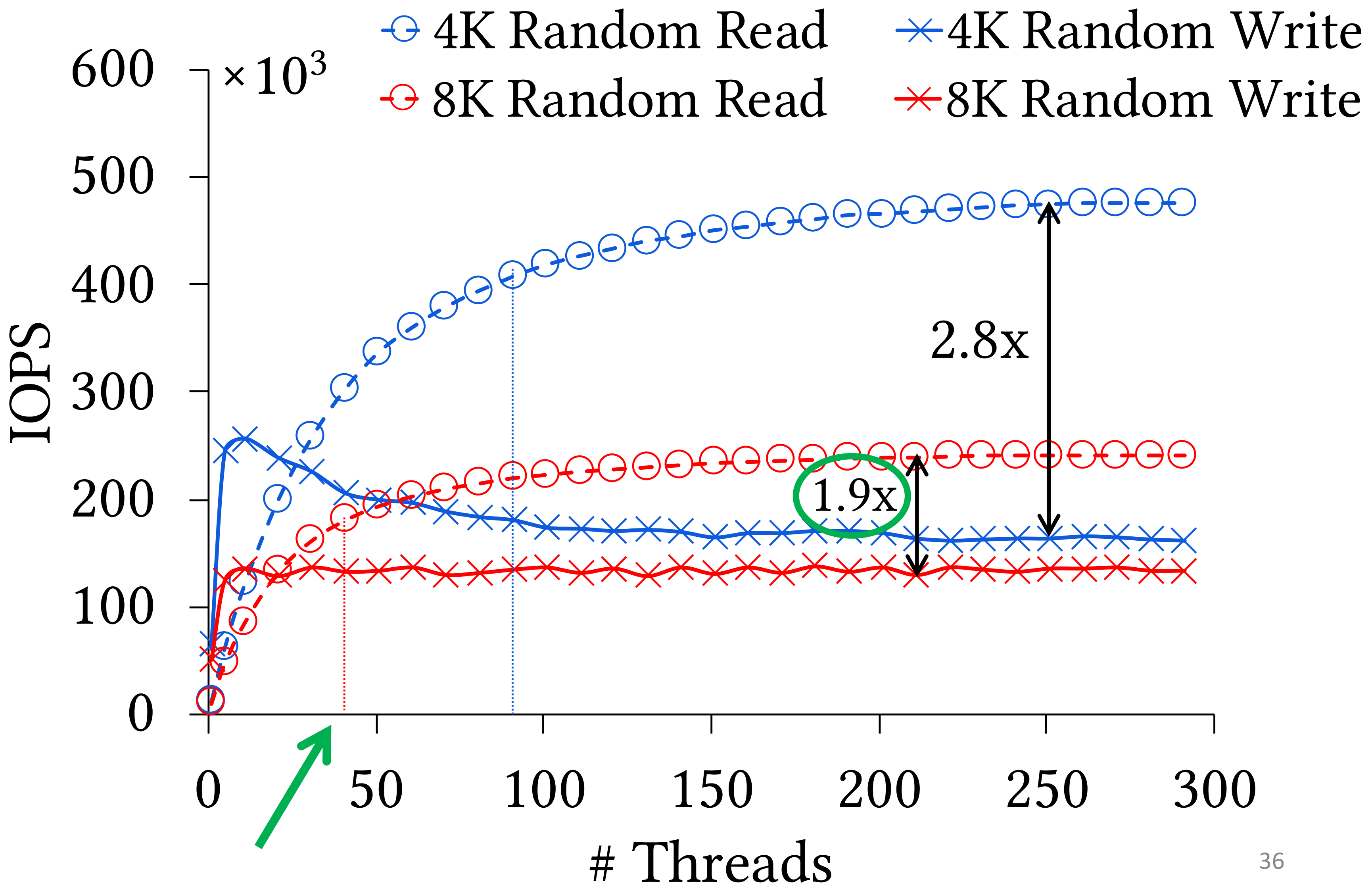
Measuring Asymmetry/Concurrency (With FS)

Device
PCIe SSD - P4510 (1TB)

For 8K random read,

Asymmetry: 1.9

Concurrency: 40



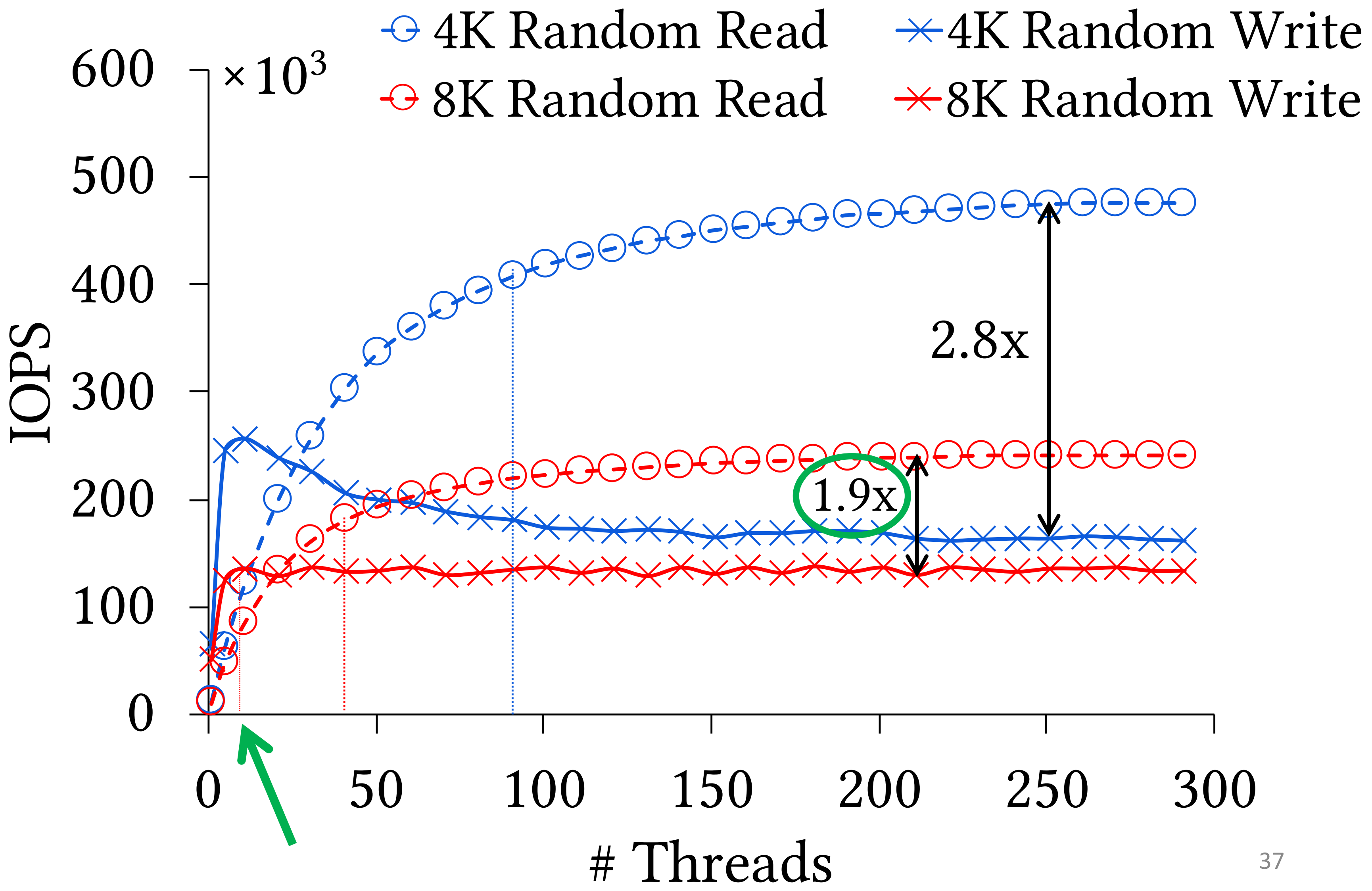
Measuring Asymmetry/Concurrency (With FS)

Device
PCIe SSD - P4510 (1TB)

For 8K random write,

Asymmetry: 1.9

Concurrency: 7

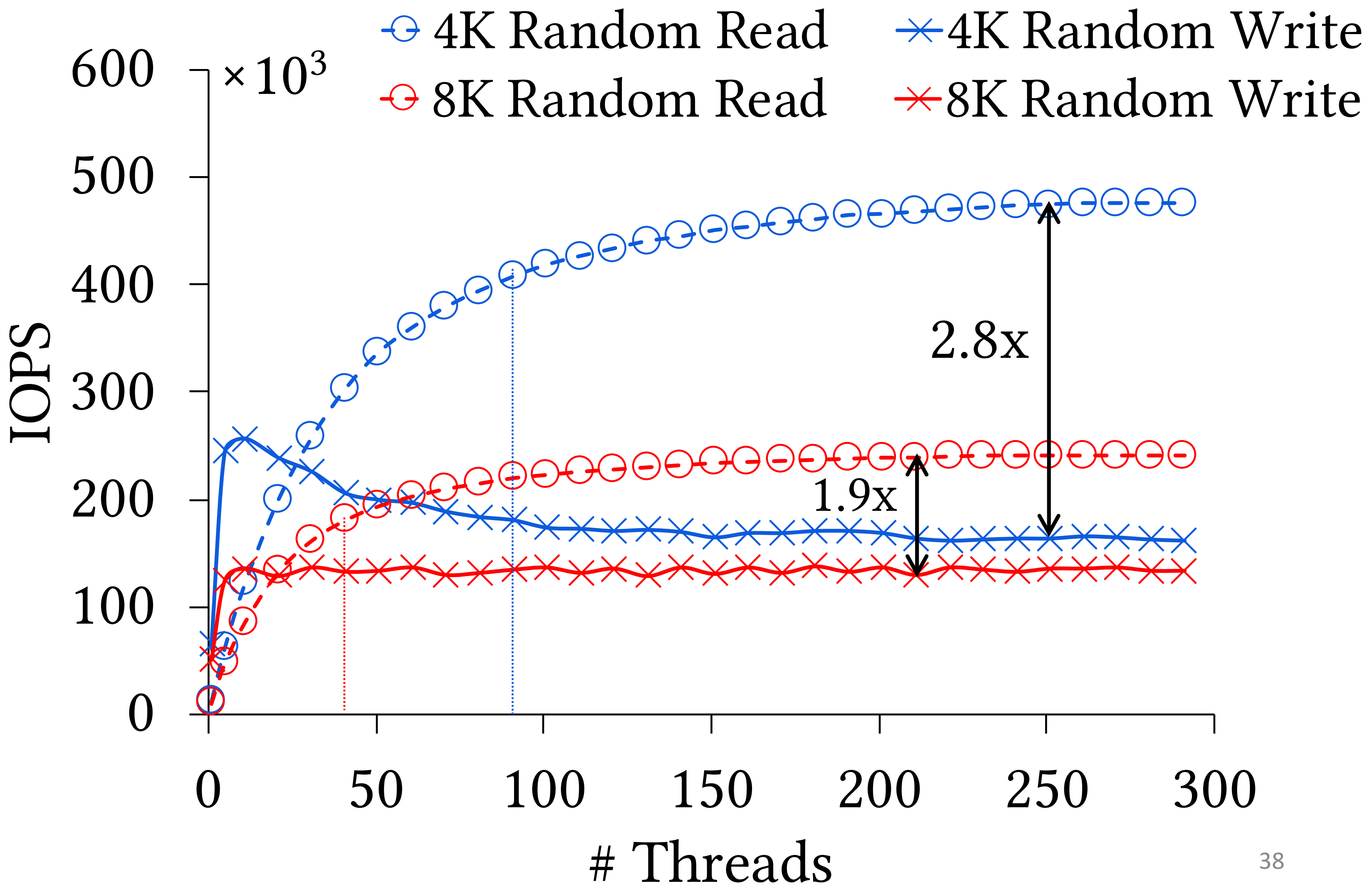


Measuring Asymmetry/Concurrency (With FS)

Device

PCIe SSD - P4510 (1TB)

Asymmetry and concurrency depends on request type and access granularity.



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Empirical Asymmetry and Concurrency

	4KB			8KB		
Devices	α	k_r	k_w	α	k_r	k_w
Optane SSD	1.1	6	5	1.0	4	4
PCIe SSD (with FS)	2.8	80	8	2.0	40	7
PCIe SSD (w/o FS)	3.0	16	6	3.0	15	4
SATA SSD	1.5	25	9	1.3	21	5
Virtual SSD	2.0	>11	>19	1.9	>6	>10

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Which module of a DBMS interacts with storage the most?

Bufferpool Manager

Buffer Pool Page Eviction Algorithm

Classical

```
Request(page);
If (page in BP) -> return page
Else
    // Miss! Bring the page from Disk
    If BP not full -> Read requested page from Disk
    Else
        - Select a page for eviction based on replacement policy
        - If the candidate page is dirty, write to disk
        - Drop the candidate page from BP
        - Read requested page
```

[if the request is a **write**, an **in-memory update** takes place that set the **dirty bit** as well]

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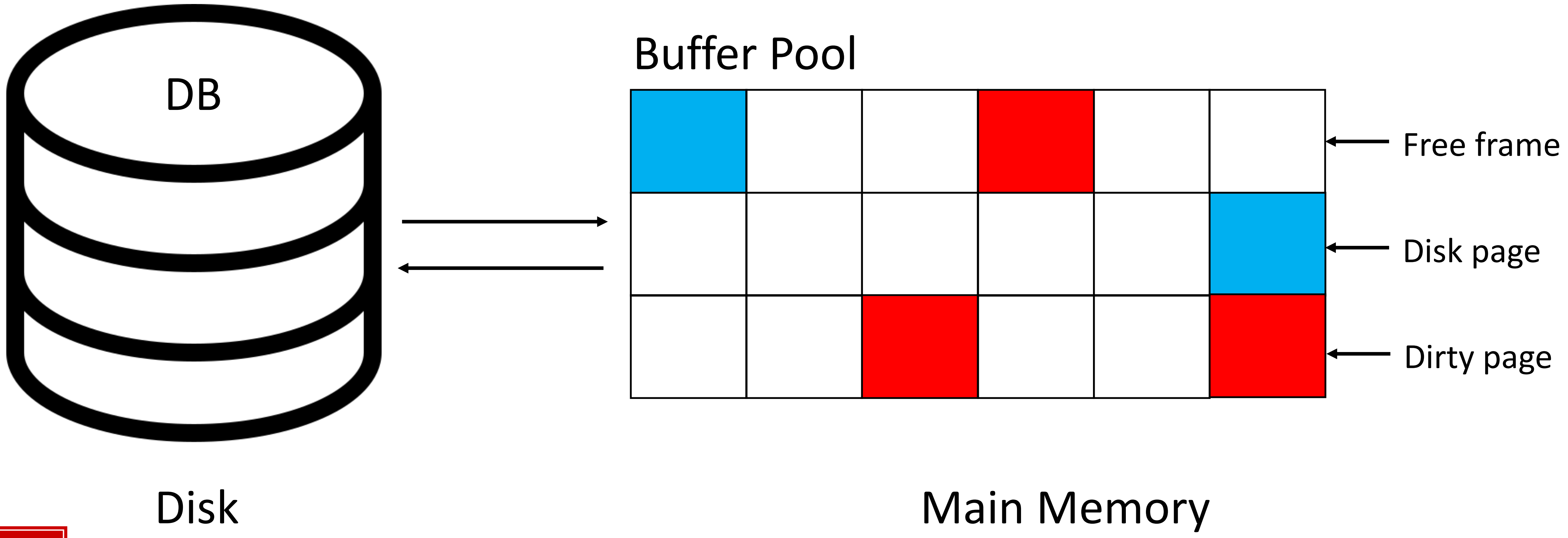
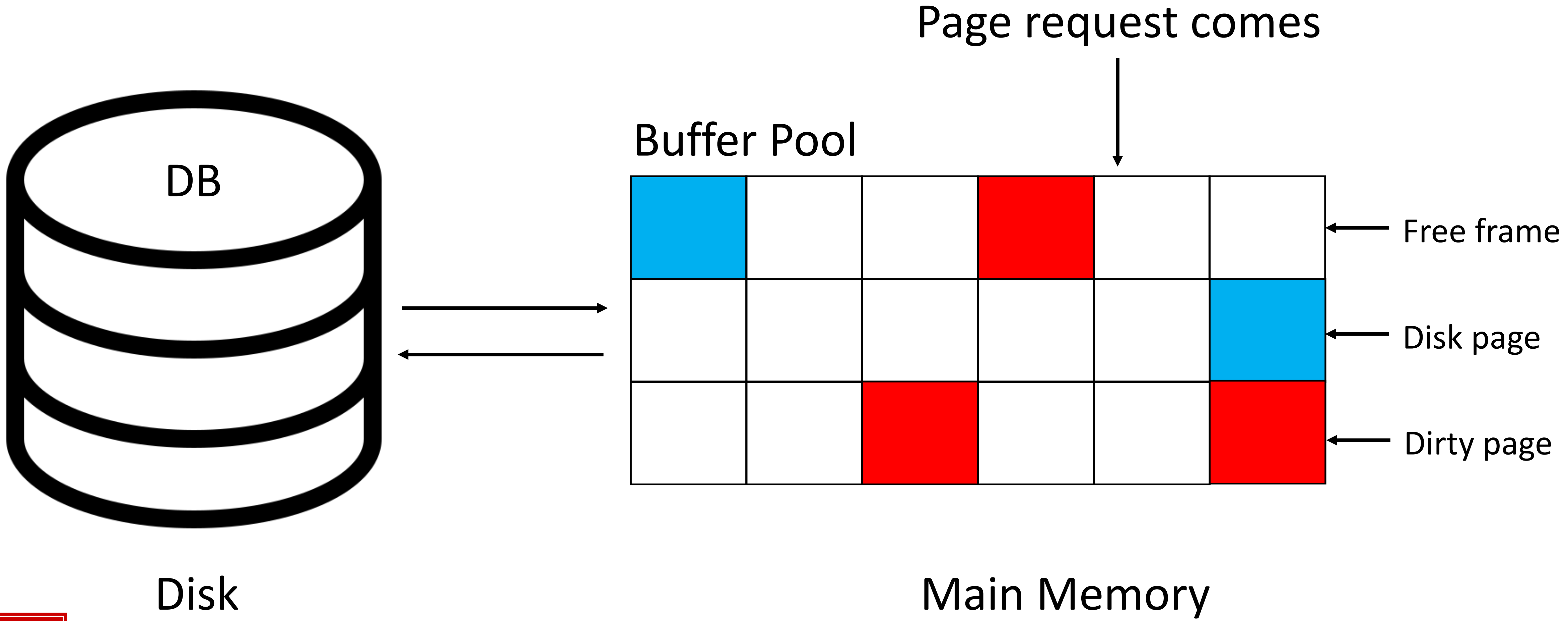
Buffer Pool Manager



Traditional Buffer Pool Manager



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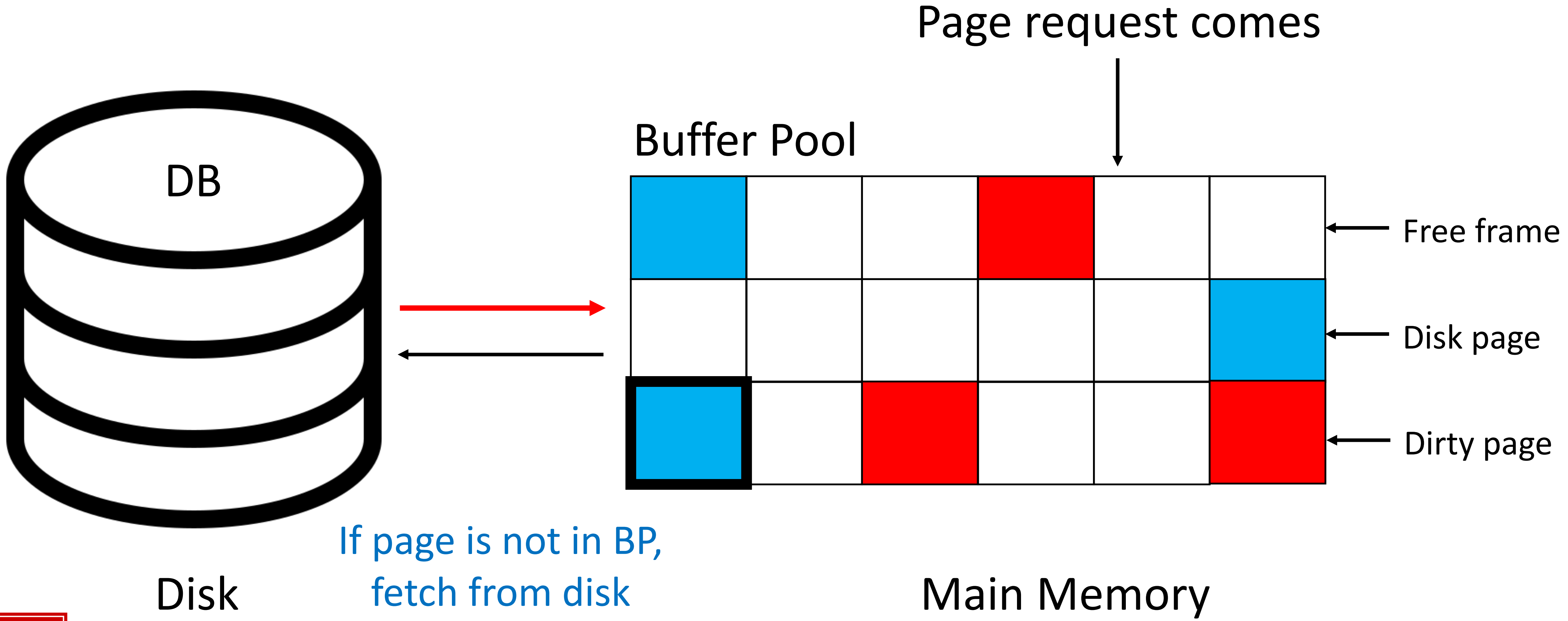

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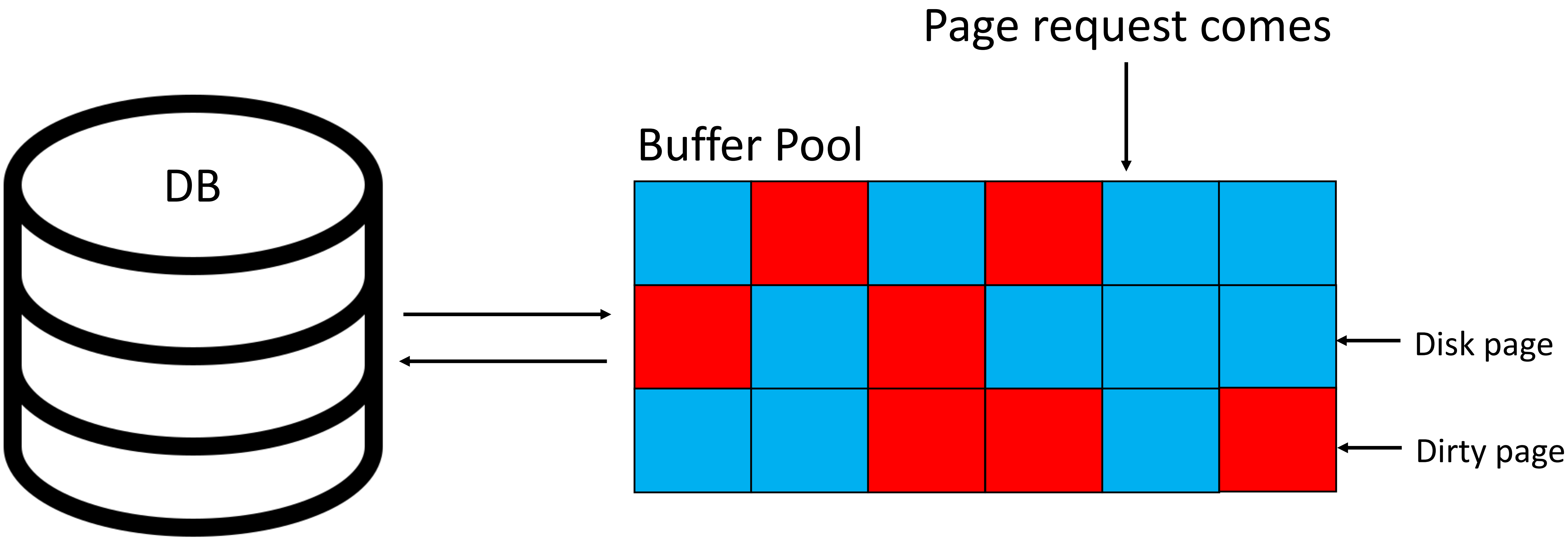
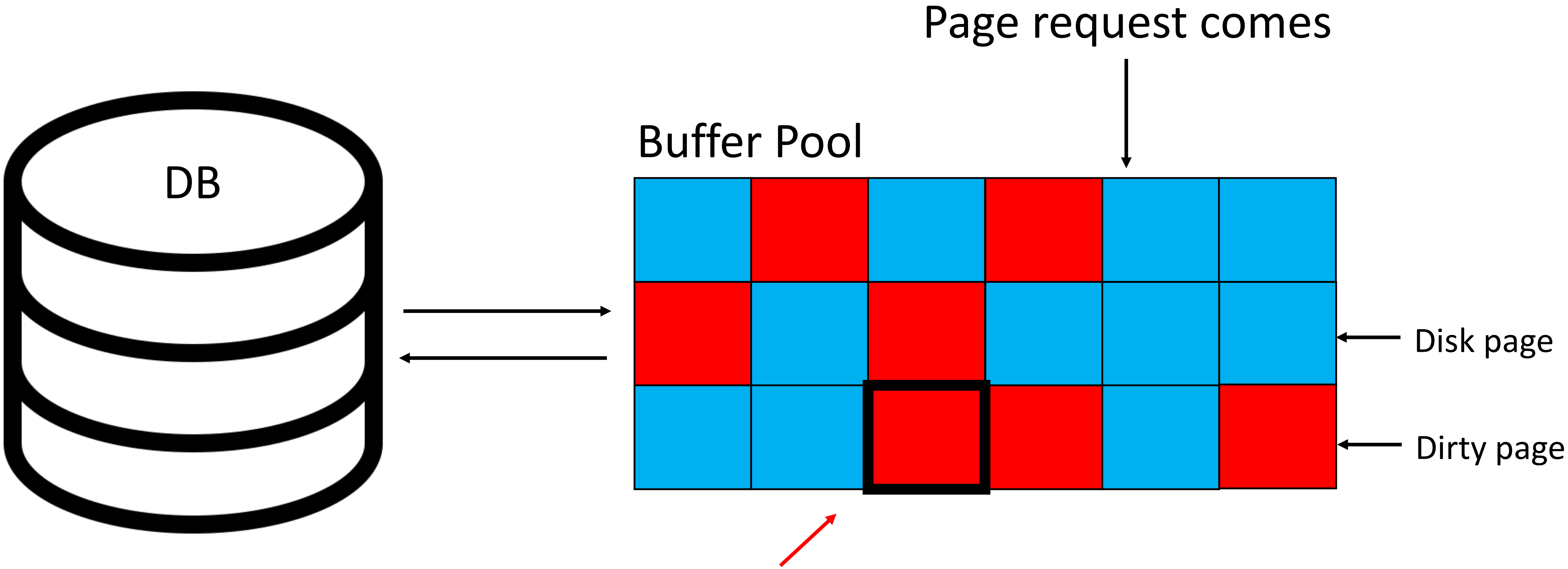


If BP is full, one page is selected for eviction based on **page replacement policy**

Traditional Buffer Pool Manager



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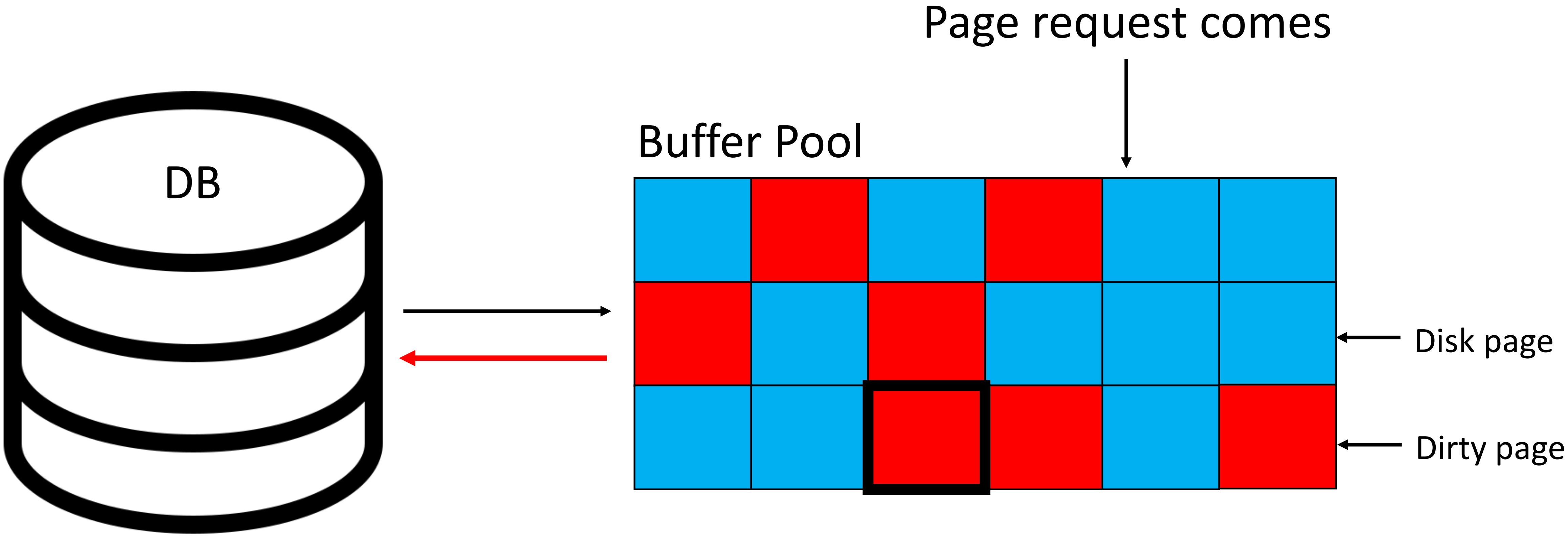

If the page is dirty, it is **written back** to disk

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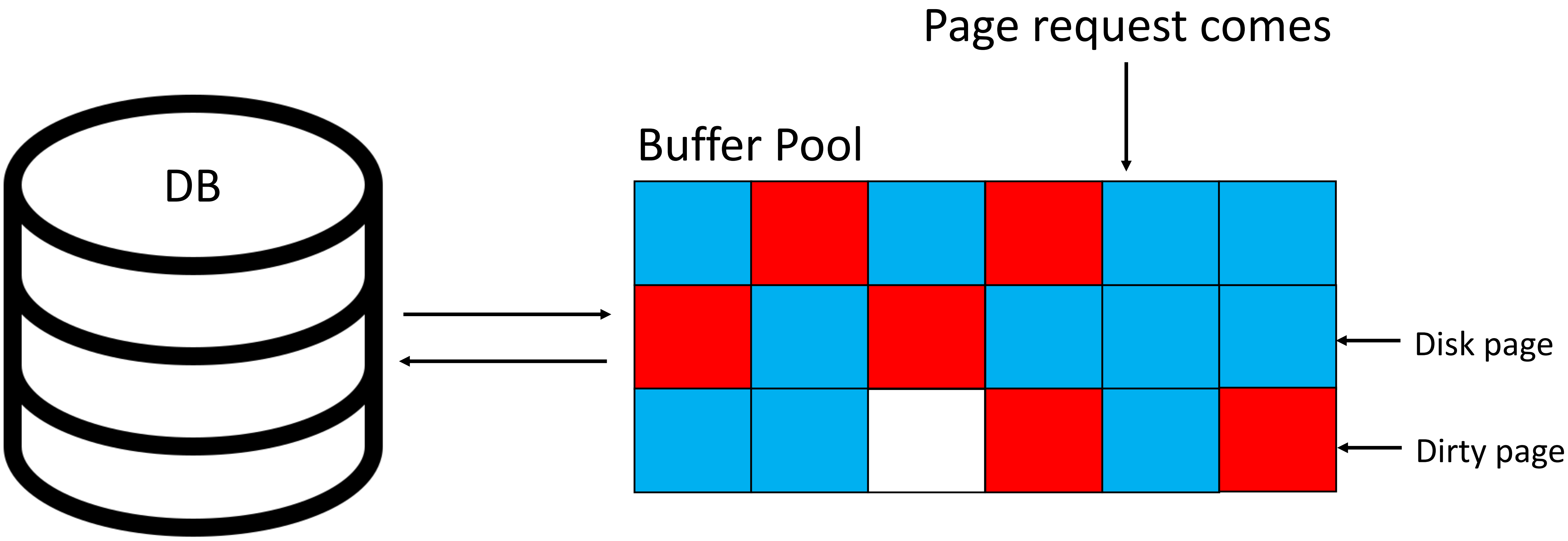
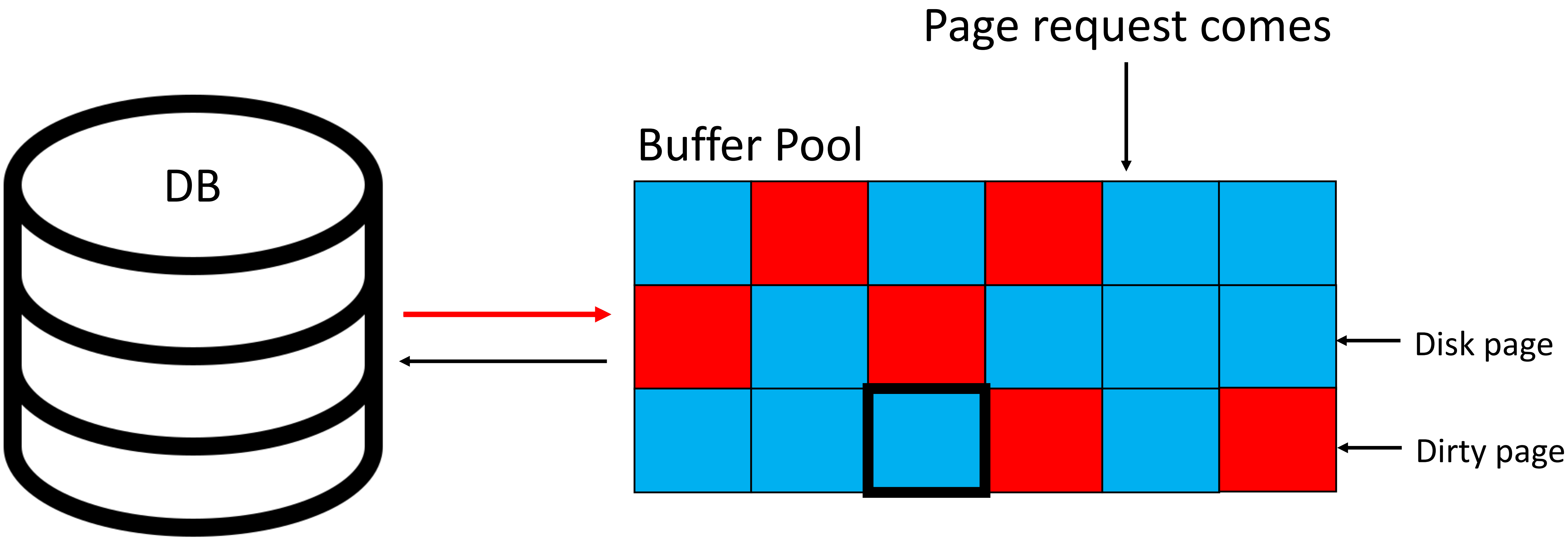
Traditional Buffer Pool Manager



If the page is dirty, it is **written back** to disk and **evicted**

Traditional Buffer Pool Manager



The requested page is fetched in its place

(exchanging one write for a read)

Popular Page Replacement Algorithms

LRU	(Most Popular)
LFU, FIFO	(Simple)
Clock Sweep	(Commercial)
CFLRU	Flash-Friendly
LRU-WSR	Flash-Friendly

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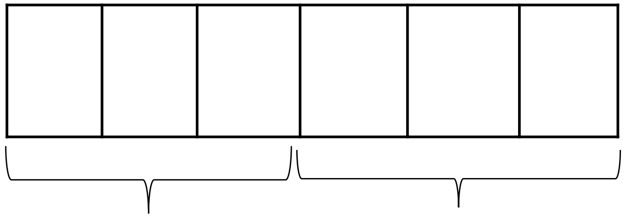
CFLRU



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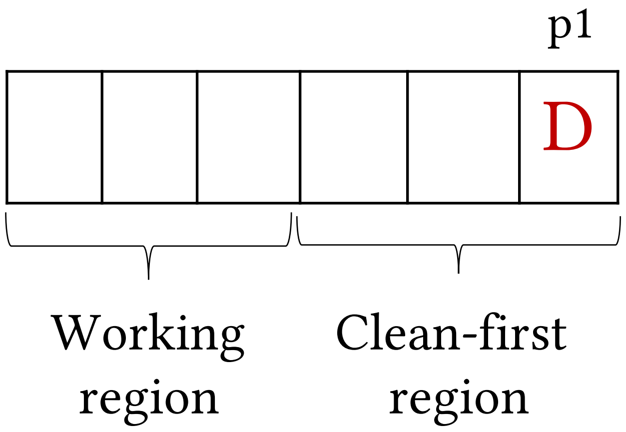
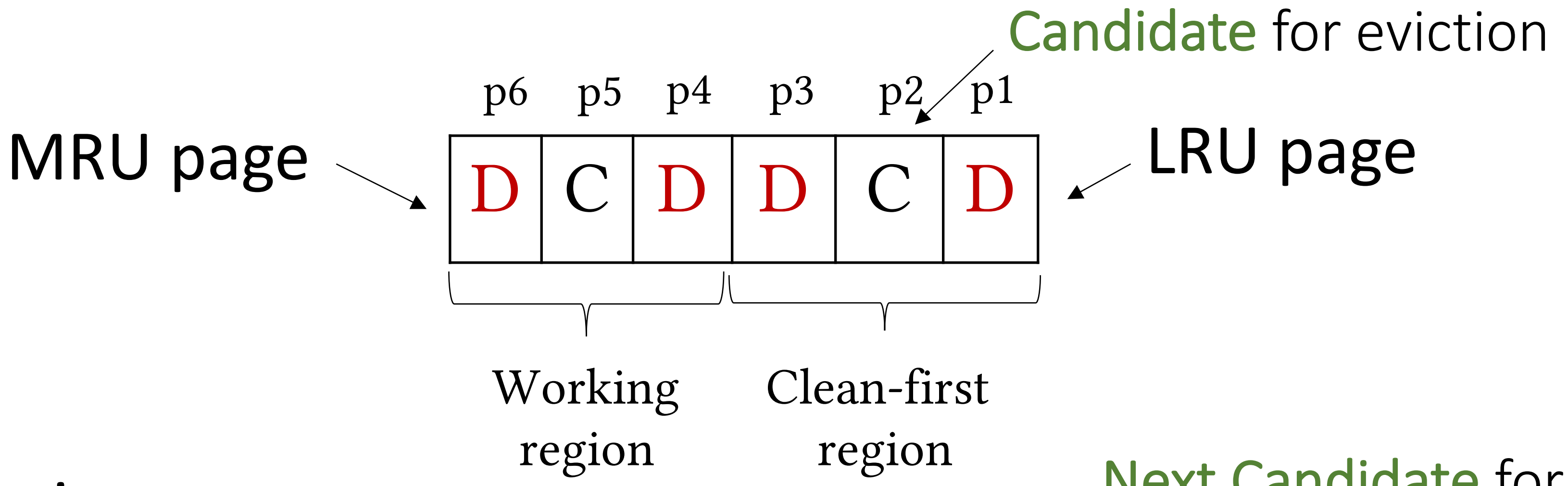
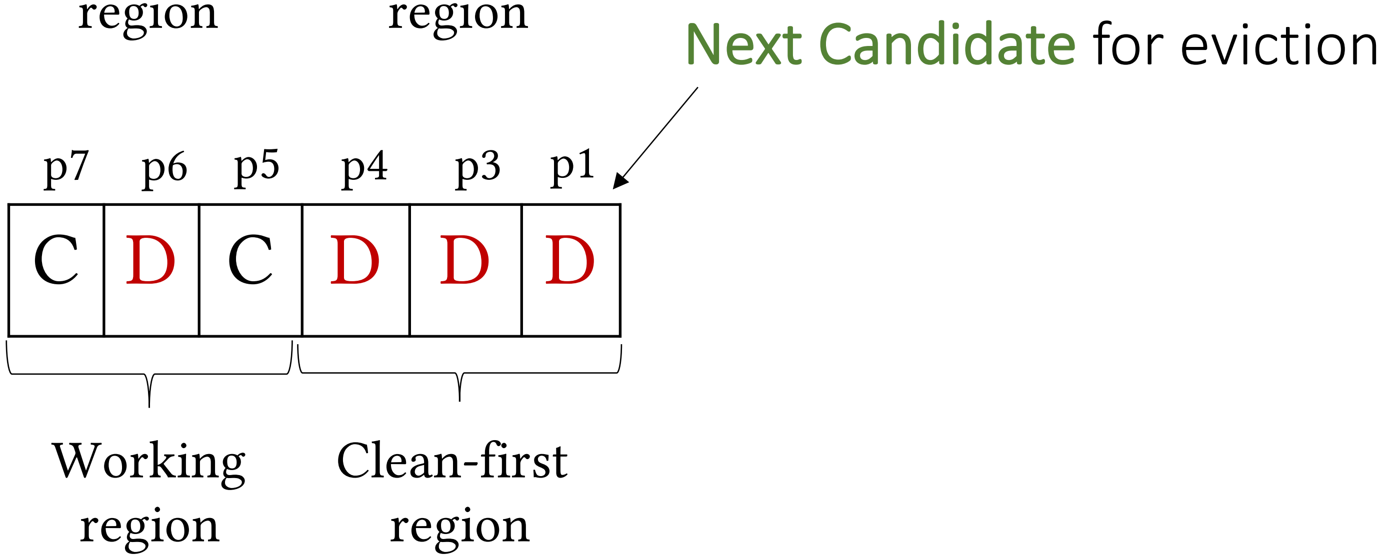
CFLRU



CFLRU



After Eviction:



LRU-WSR

	p6	p5	p4	p3	p2	p1
	D	C	D	D	C	D
Cold flag	1		0	0		0

← Cold flag NOT set! This is be moved to front setting the cold flag

	p1	p6	p5	p4	p3	p2
	D	D	C	D	D	C
Cold flag	1	1		0	0	

← Candidate for eviction

After Eviction:

	p7	p1	p6	p5	p4	p3
	C	D	D	C	D	D
Cold flag		1	1		0	0

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LRU-WSR

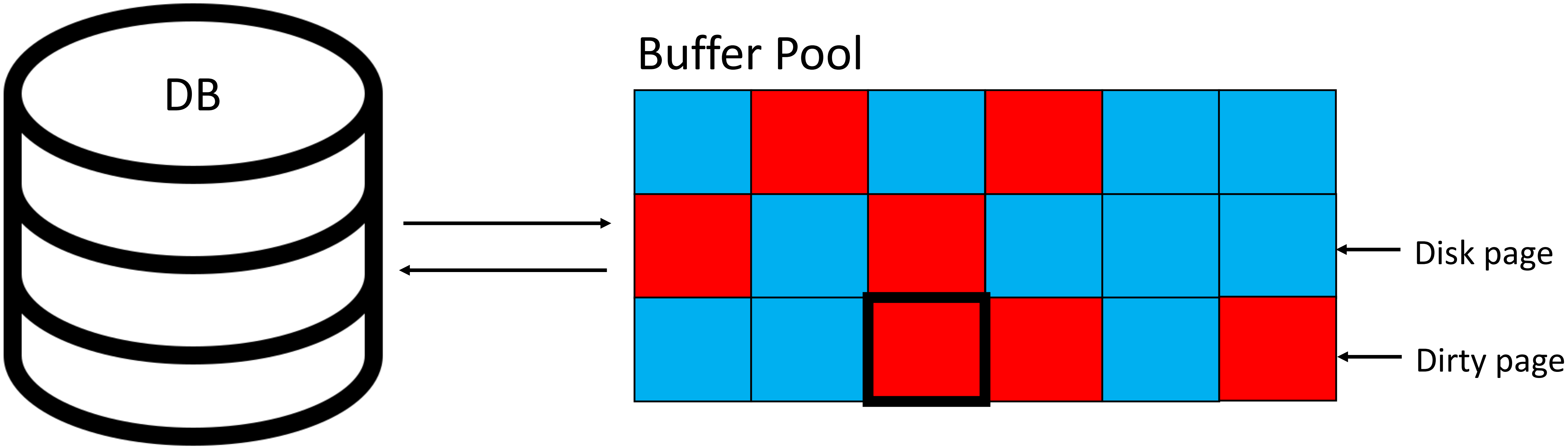
	p6	p5	p4	p3	p2	p1
	D	C	D	D	C	D
Cold flag	1		0	0		1

Cold flag set!
Candidate for eviction

After Eviction:

	p7	p6	p5	p4	p3	p2
	C	D	C	D	D	C
Cold flag		1		0	0	

The Challenge

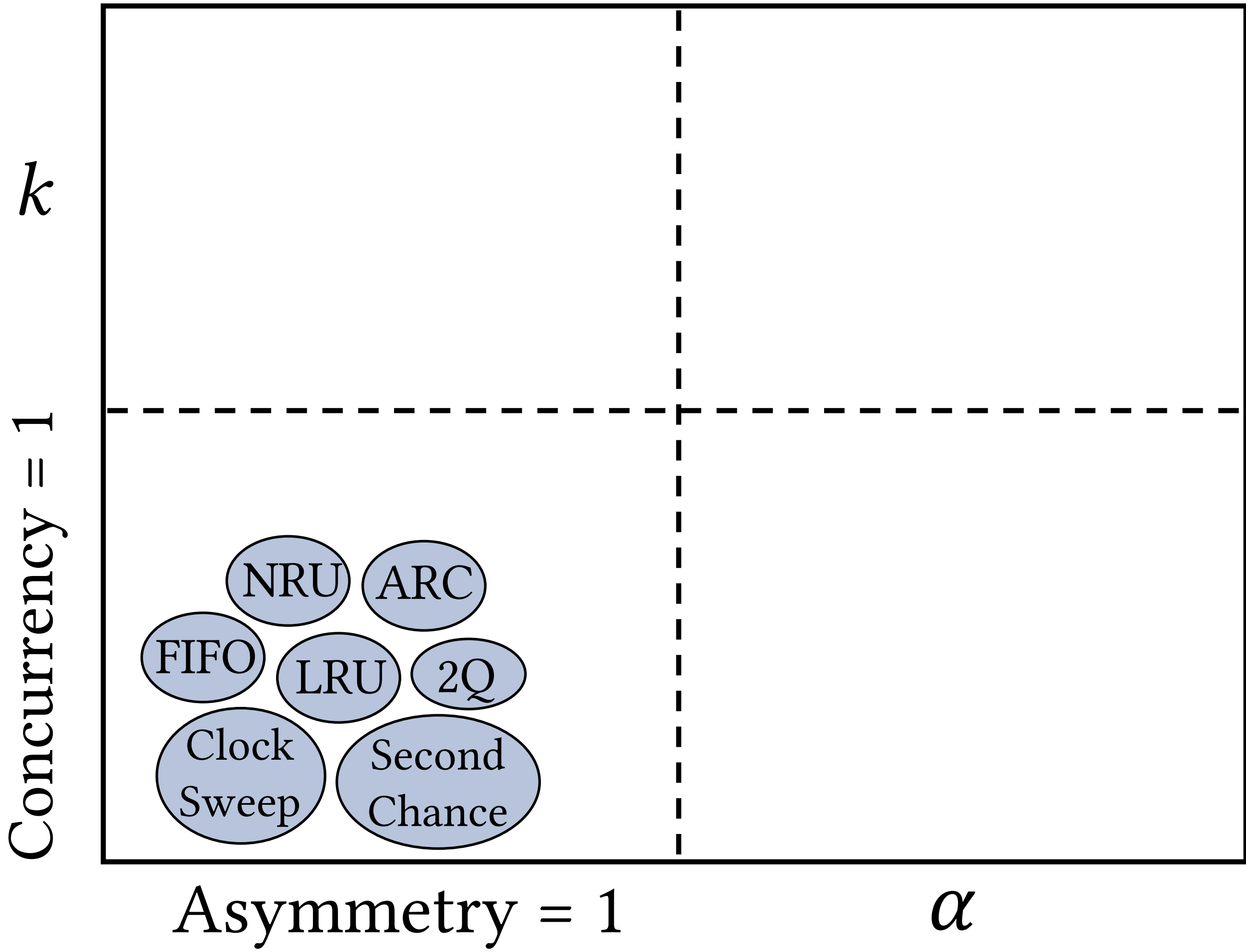


All these policies exchange one read for one write!

Is this Fair?

The Challenge

- (Challenge 1) With write asymmetry, it is **NOT** fair to *exchange one write for one read*.



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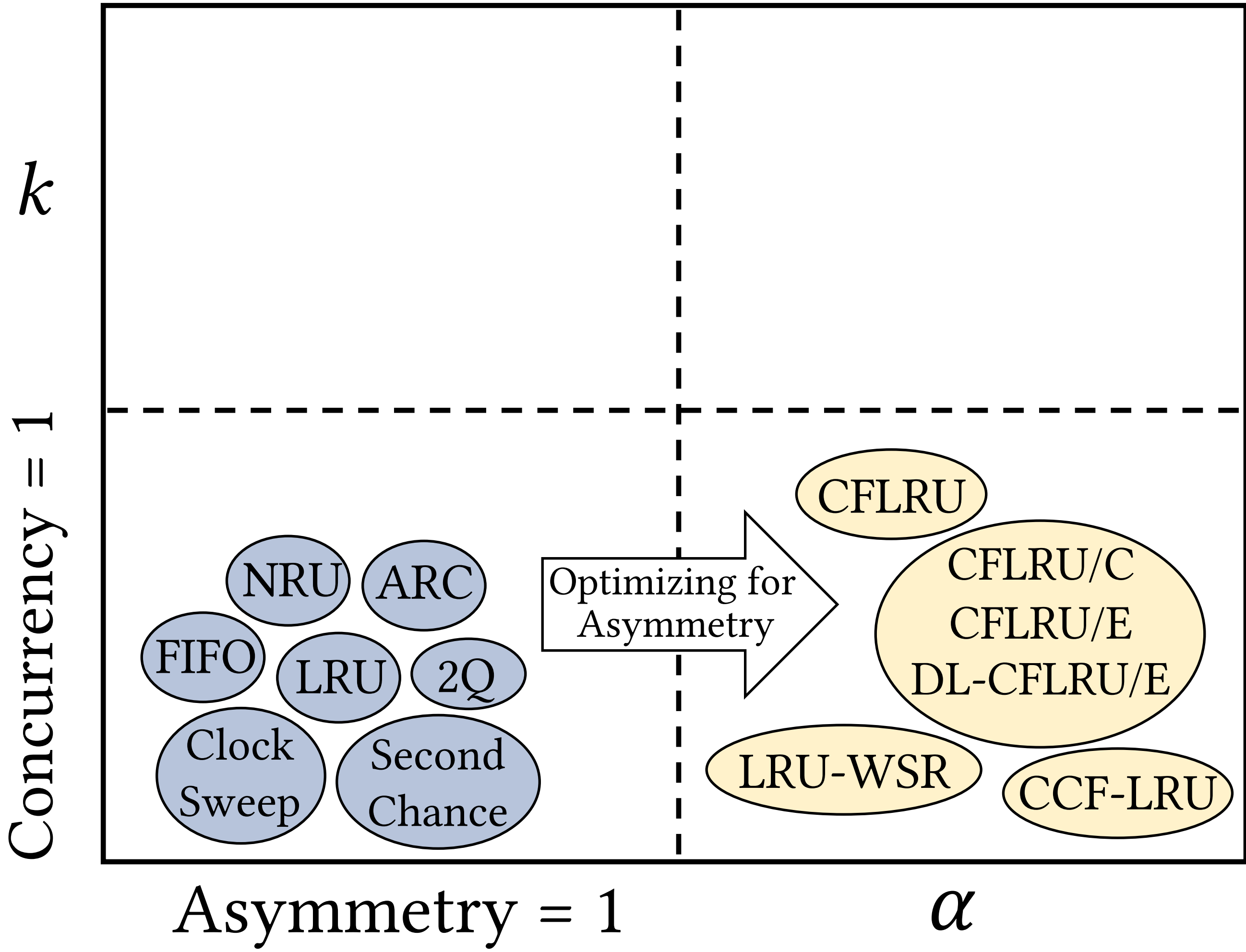

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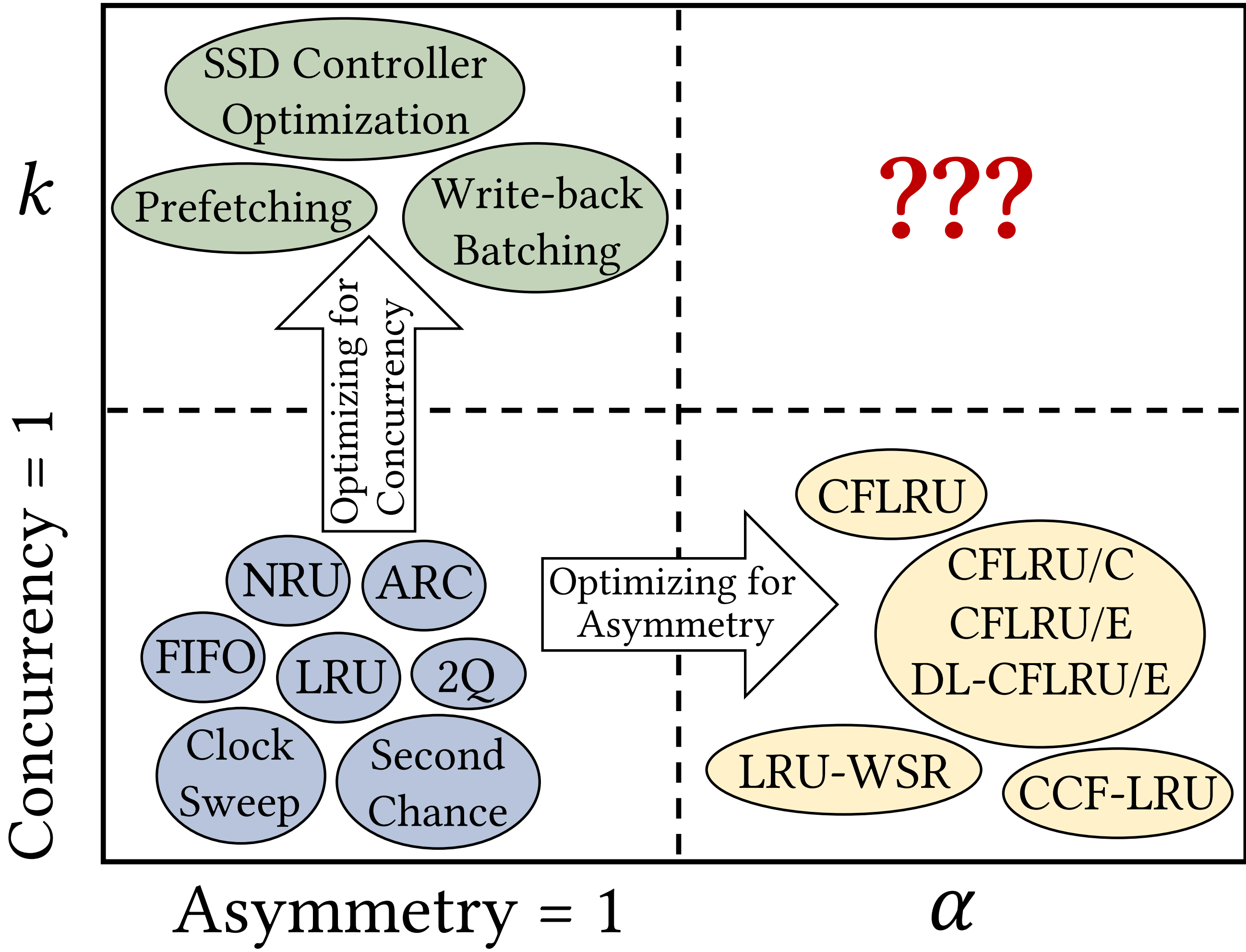
The Challenge

- (Challenge 1) With write asymmetry, it is **NOT** fair to *exchange one write for one read*.
- (Challenge 2) Bufferpool Managers do **NOT** expressly utilize the *device concurrency*.



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The Challenge

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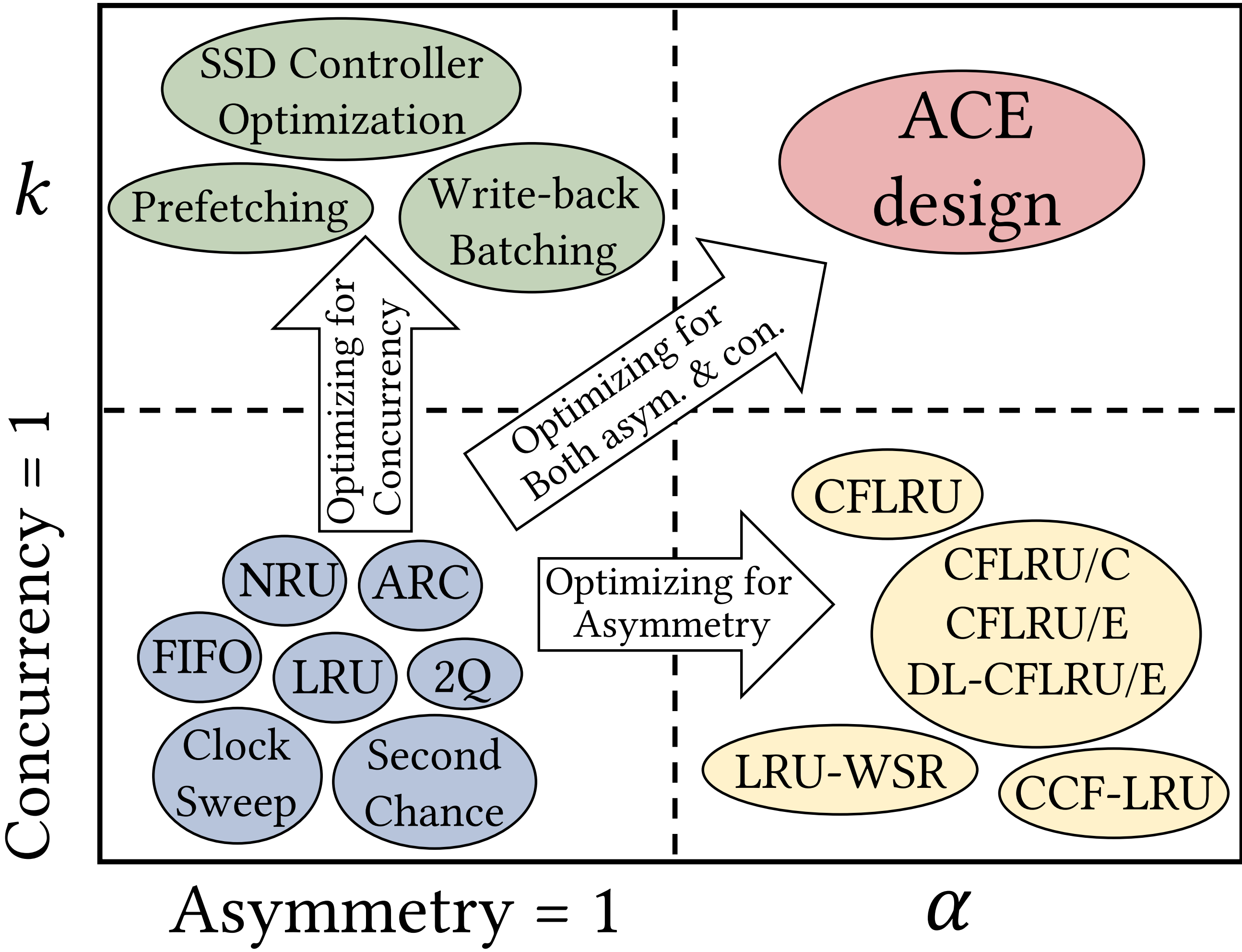

Bufferpool Design Space

Classical Bufferpool Design Space

Bufferpool Manager

Eviction Policy

Which page to evict?

- LRU
- NRU
- Clock
- Second Chance
- FIFO
- 2Q
- ARC

- CFLRU
- LRU-WSR
- CCF-LRU
- CFLRU/C
- CFLRU/E
- DL-CFLRU/E

Flash-friendly policies

Read-ahead Policy (Optional)

When to prefetch?

- Prefetch on miss

Which pages?

- Sequential/
- History-based

How many pages?

- 1 or x pages

How to prefetch?

- Sequentially

Bufferpool Design Space

Bufferpool Manager

Red indicates new design elements

Eviction Policy

How many pages to evict?

Which pages to evict?

- LRU
- NRU
- Clock
- Second Chance
- FIFO
- 2Q
- ARC

Flash-friendly policies:

- CFLRU
- LRU-WSR
- CCF-LRU
- CFLRU/C
- CFLRU/E
- DL-CFLRU/E

Write-back Policy

How many pages to flush?

- 1 page
- *n* pages (exploit k_w)

Which pages to flush?

- dirty pages following replacement algo.

How to write?

- one-at-a-time vs. concurrently

Read-ahead Policy (Optional)

When to prefetch?

- Prefetch on miss

Which pages?

- Sequential
- History-based

How many pages?

- 1 or *x* pages

How to prefetch?

- Seq./Concurrently

Asymmetry/Concurrency-Aware (ACE) Bufferpool Manager

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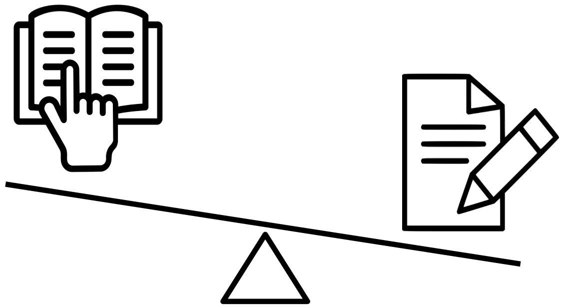
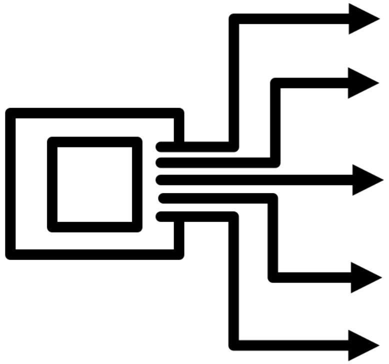
ACE Bufferpool Manager

Use device's properties





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ACE Bufferpool Manager

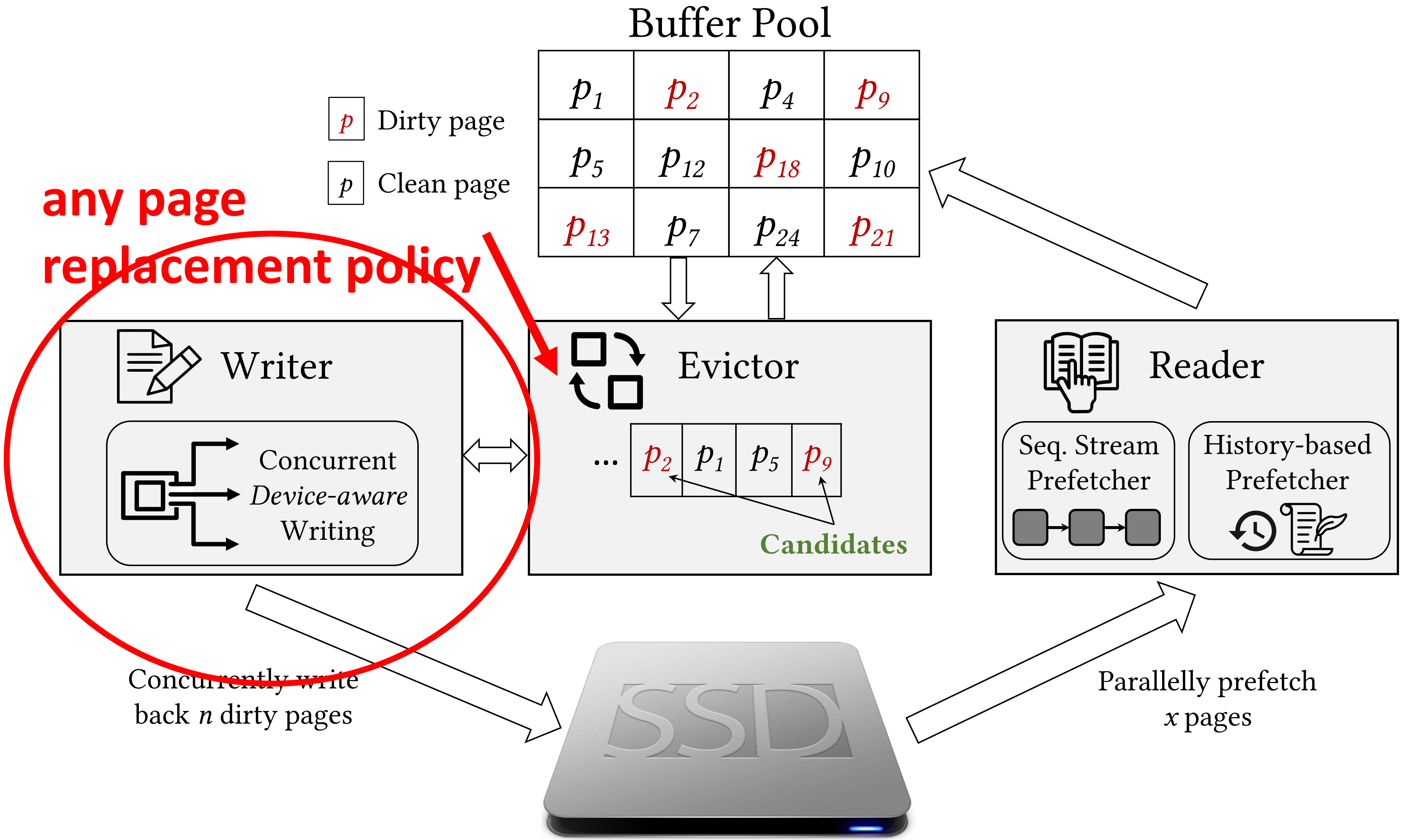
Flush multiple **dirty** pages **concurrently**

Evict 1 page (to not disrupt locality)
or
Evict multiple pages (if we trust prefetching)

Goal: 1 read vs. α concurrent write backs (more if concurrency permits)

ACE Bufferpool Manager

any page replacement policy



with PF

w/o PF

Buffer Pool Page Eviction Algorithm

```
Request(page pR);
If (page in BP) -> return page
Else
    // Miss! Bring the page from Disk
    If BP not full -> Read requested page from Disk
    Else
        - Select a page pE for eviction (?) based on replacement policy
        - …
```

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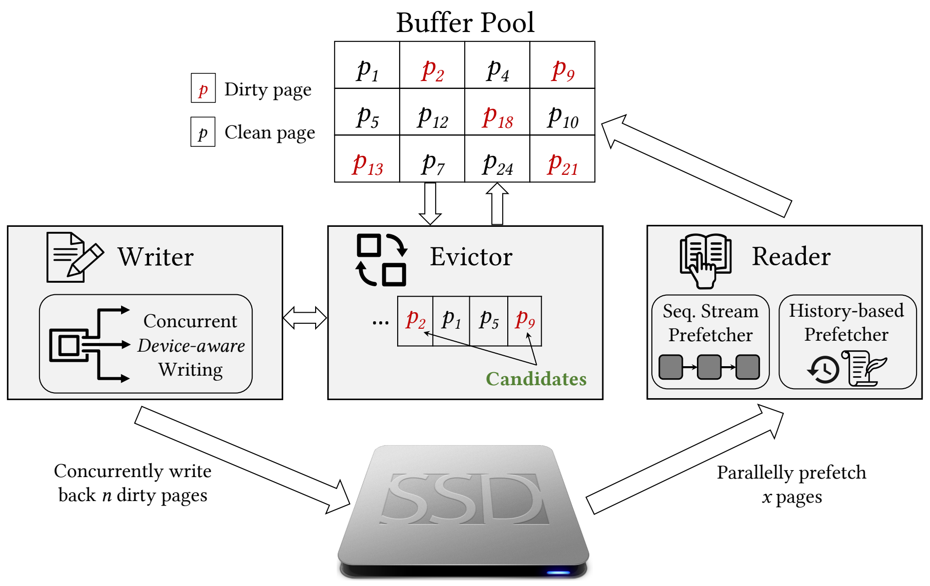
Module: Writer

Concurrent write-back

- If $\mathbf{p_E}$ is dirty, then write *n* dirty pages concurrently

  where, *n* = device's write concurrency (k_w)
- If $\mathbf{p_E}$ is clean, skip to Evictor



The *n* pages are selected following the order of the underlying page replacement algorithm

Module: Evictor

Piggy-backs on the underlying replacement algorithm

If **prefetching is not enabled**

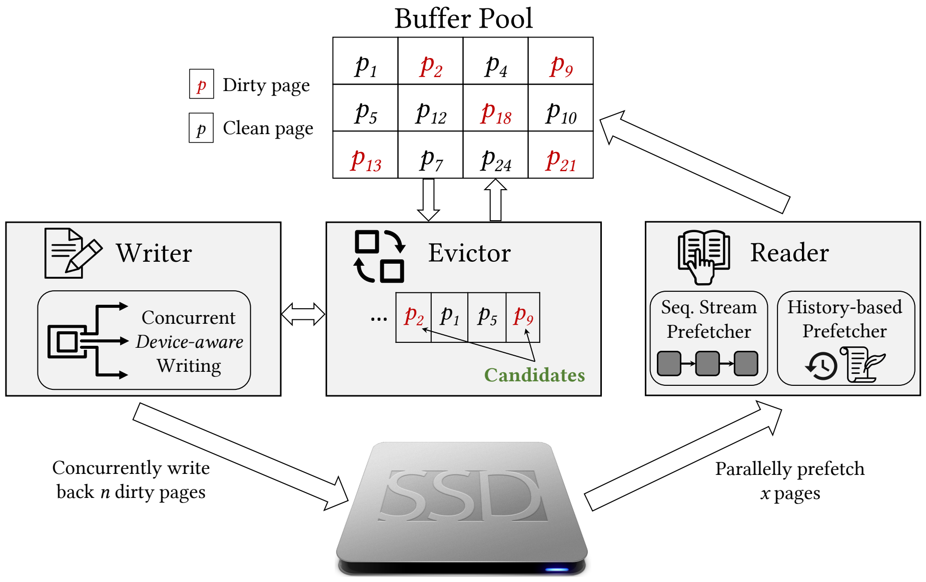
✓ Evict 1 page (following the replacement algorithm)

If **prefetching is enabled** & $\mathbf{p_E}$ is clean

✓ Evict 1 page

If **prefetching is enabled** & $\mathbf{p_E}$ is dirty

✓ Evict n pages



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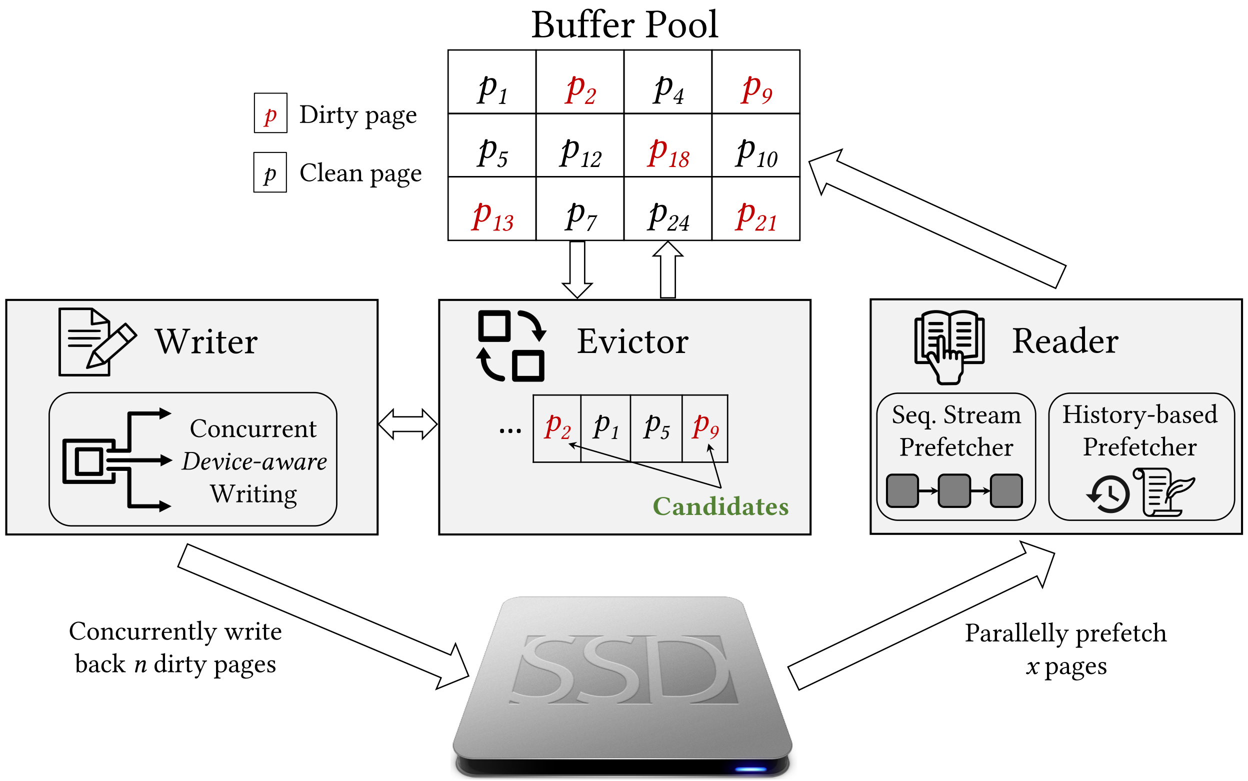
Module: Reader

Fetch the **requested page $\mathbf{p_E}$**

If prefetching is enabled (n pages were evicted)

✓ Prefetch **concurrently** *n-1* pages

- Sequential prefetcher
- History-based prefetcher



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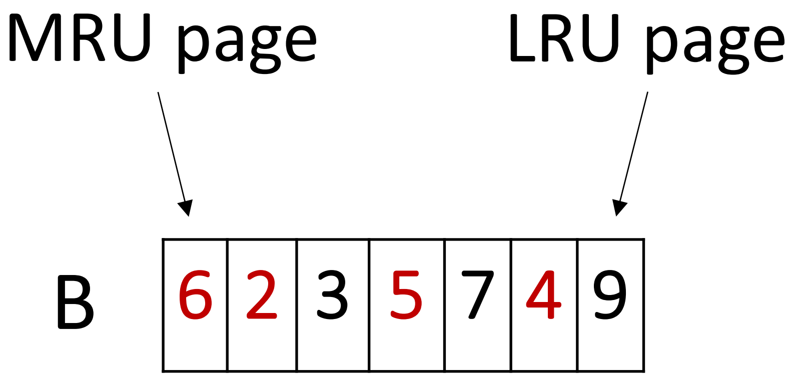
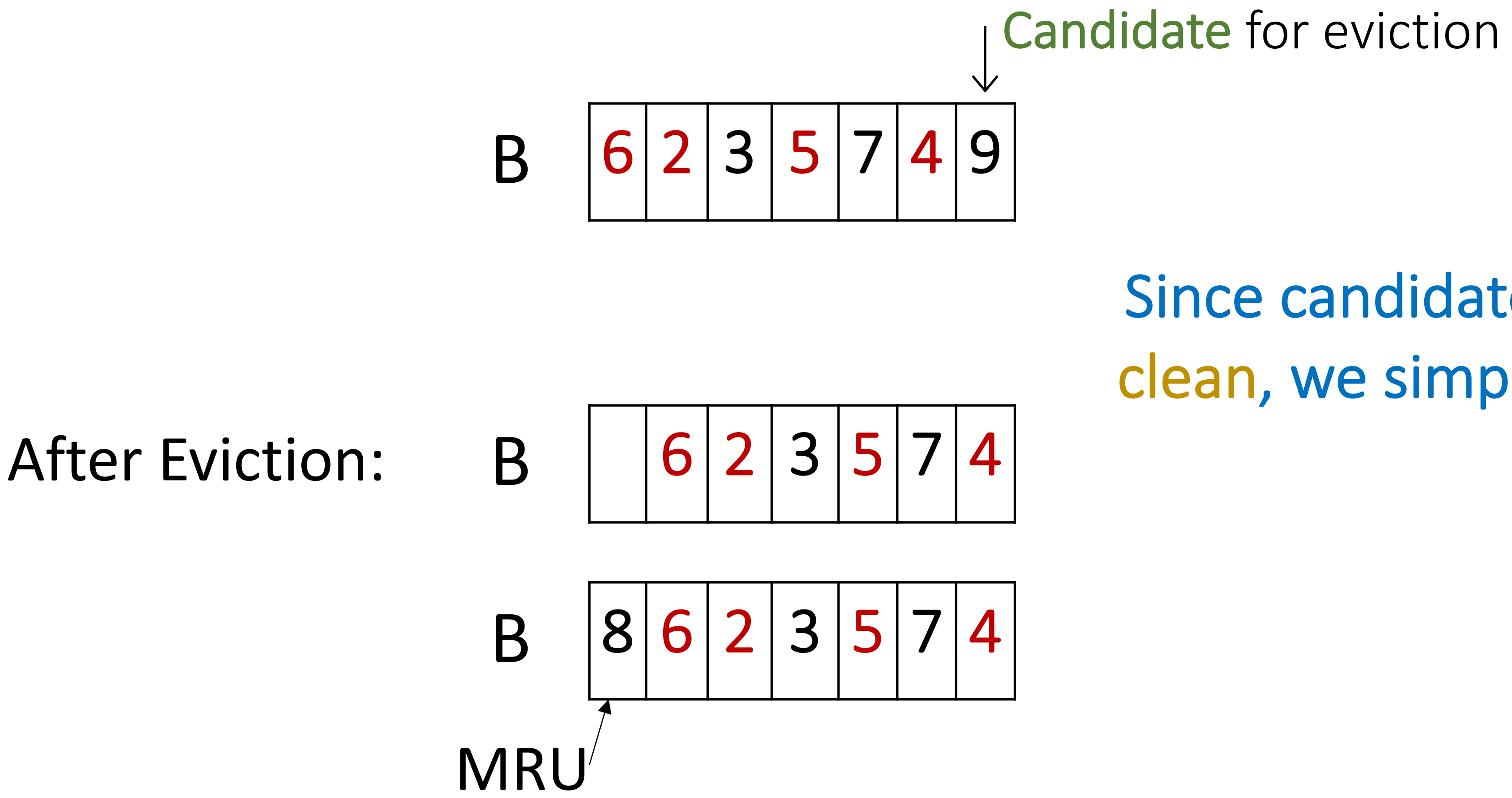
Let’s Take a Look at an Example



Let’s assume: $\alpha = 3$, LRU is the baseline replacement policy & red indicates dirty page

Next, a read request for page 8 arrives

Let's Take a Look at an Example



Since candidate page is clean, we simply evict it

Next, a write request for page 1 arrives

Let's Take a Look at an Example ($\alpha = 3$)

LRU

B	8	6	2	3	5	7	4 (Candidate)

Eviction:

evict candidate (4)

B		8	6	2	3	5	7
B	1	8	6	2	3	5	7

Let’s Take a Look at an Example (α = 3)

LRU

Candidate ↓ (4)

B	8	6	2	3	5	7	4

Eviction:
evict candidate (4)

B		8	6	2	3	5	7

B	1	8	6	2	3	5	7

ACE LRU(w/o PF)

Candidate ↓ (4)

B	8	6	2	3	5	7	4

Write-back: 2,5,4 concurrently written

Eviction: 4 is evicted

B		8	6	2	3	5	7

B	1	8	6	2	3	5	7

Let’s Take a Look at an Example ($\alpha = 3$)

LRU

Candidate ↓

B | 8 | 6 | 2 | 3 | 5 | 7 | 4 |

Eviction:
evict candidate (4)

B | | 8 | 6 | 2 | 3 | 5 | 7 |

B | 1 | 8 | 6 | 2 | 3 | 5 | 7 |

ACE LRU(w/o PF)

Candidate ↓

B | 8 | 6 | 2 | 3 | 5 | 7 | 4 |

Write-back: 2,5,4 concurrently written

Eviction: 4 is evicted

B | | 8 | 6 | 2 | 3 | 5 | 7 |

B | 1 | 8 | 6 | 2 | 3 | 5 | 7 |

ACE LRU(w/ PF)

Eviction Window ↓

B | 8 | 6 | 2 | 3 | 5 | 7 | 4 |

Write-back: 2,5,4 concurrently

Eviction: 5,7,4 is evicted

Prefetch: 9,0 (as LRU)

B | | 8 | 6 | 2 | 3 | 9 | 0 |

B | 1 | 8 | 6 | 2 | 3 | 9 | 0 |

Evaluation

Experimental Evaluation

- Implementation in PostgreSQL
- Clock, LRU, CFLRU, LRU-WSR vs. their ACE counterparts
- Evaluation on 4 synthesized traces and TPC-C benchmark
- 3 storage devices: NVMe SSD, $\alpha = 3$, $k_w = 8$; Regular SSD, $\alpha = 1.5$, $k_w = 8$; Virtual SSD, $\alpha = 2$, $k_w > 19$

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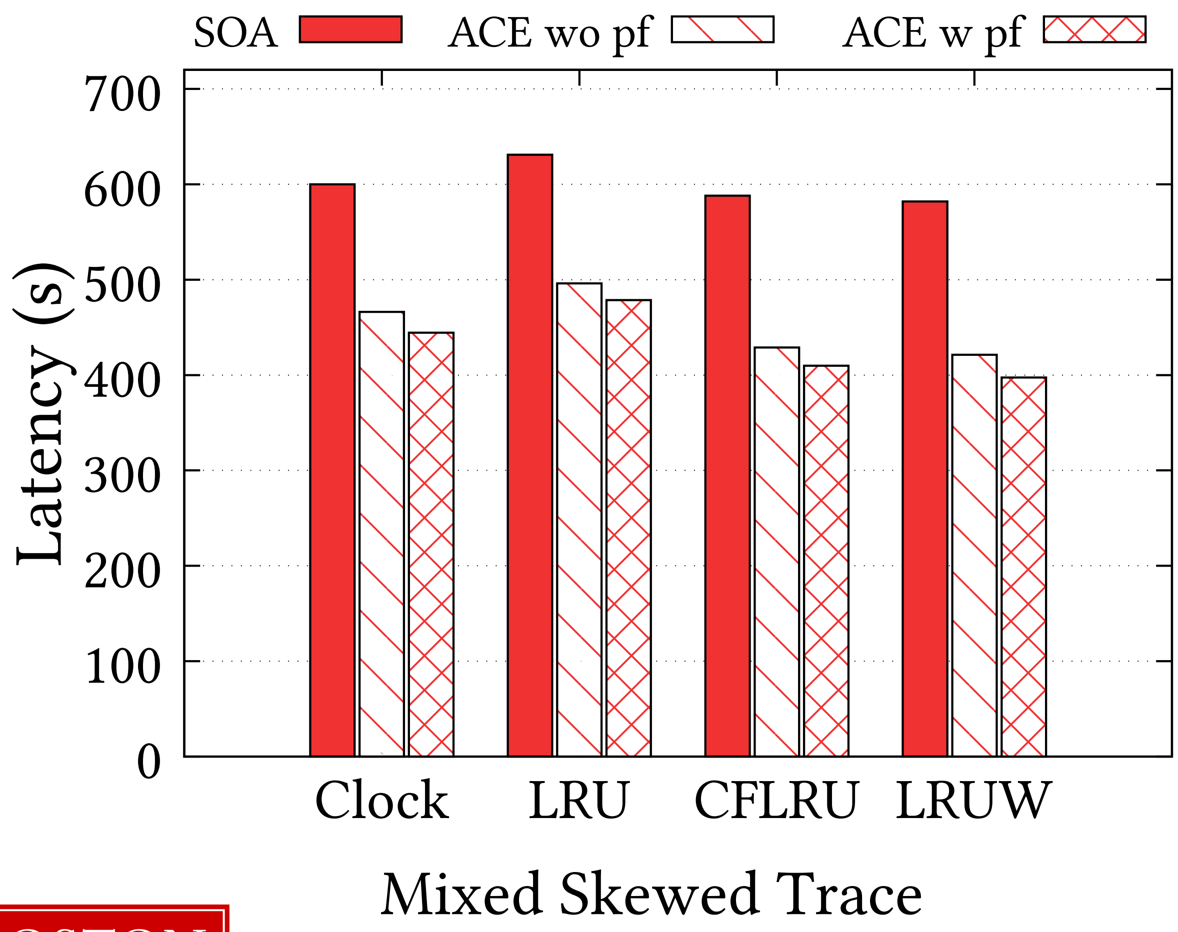
Experimental Evaluation

Device: NVMe SSD

$\alpha = 3$, $k_w = 8$



ACE improves runtime by >20%

(for a mixed skewed workload)

Negligible increase in buffer miss (<0.004%)

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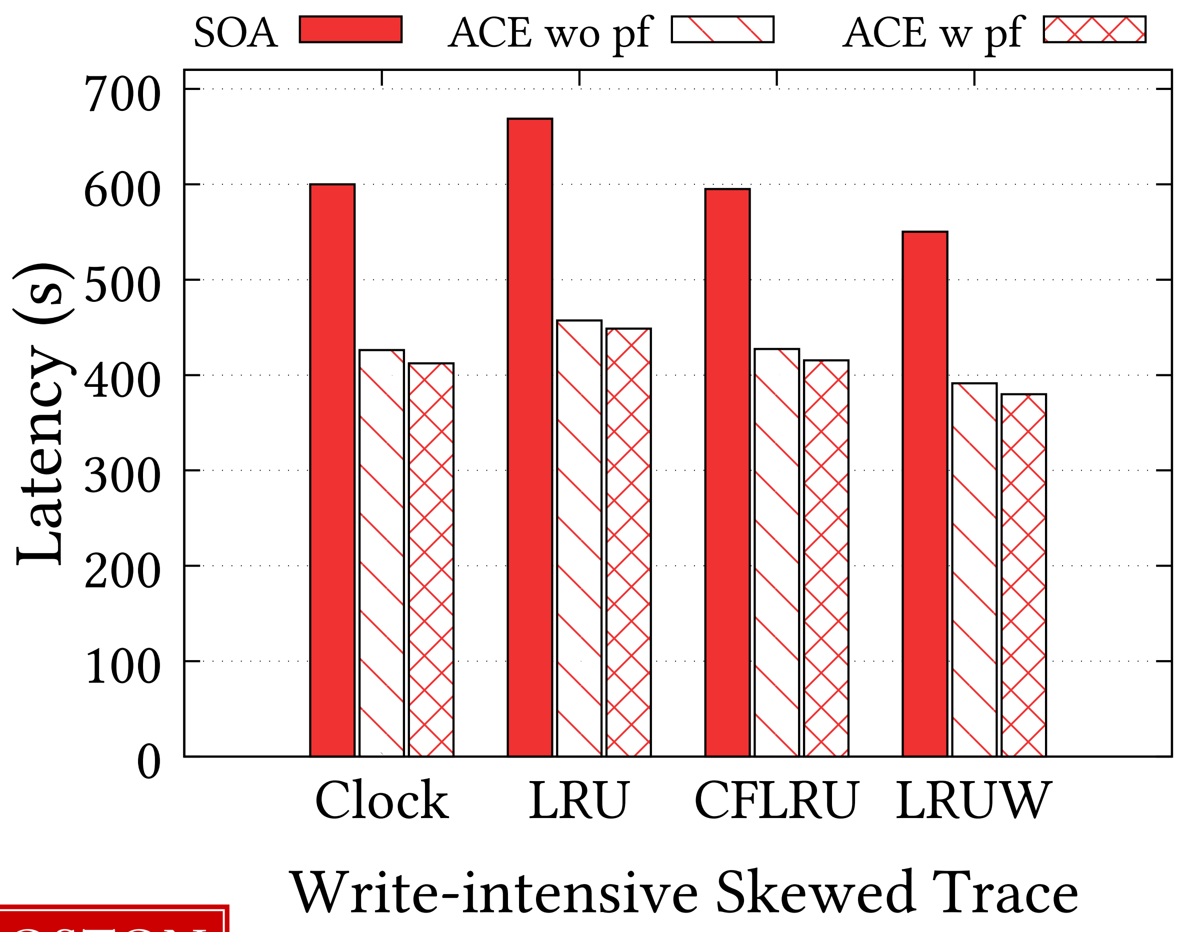
Experimental Evaluation

Device: NVMe SSD

$\alpha = 3$, $k_w = 8$



Higher gain (>30%) for write-intensive workloads because of smart batching

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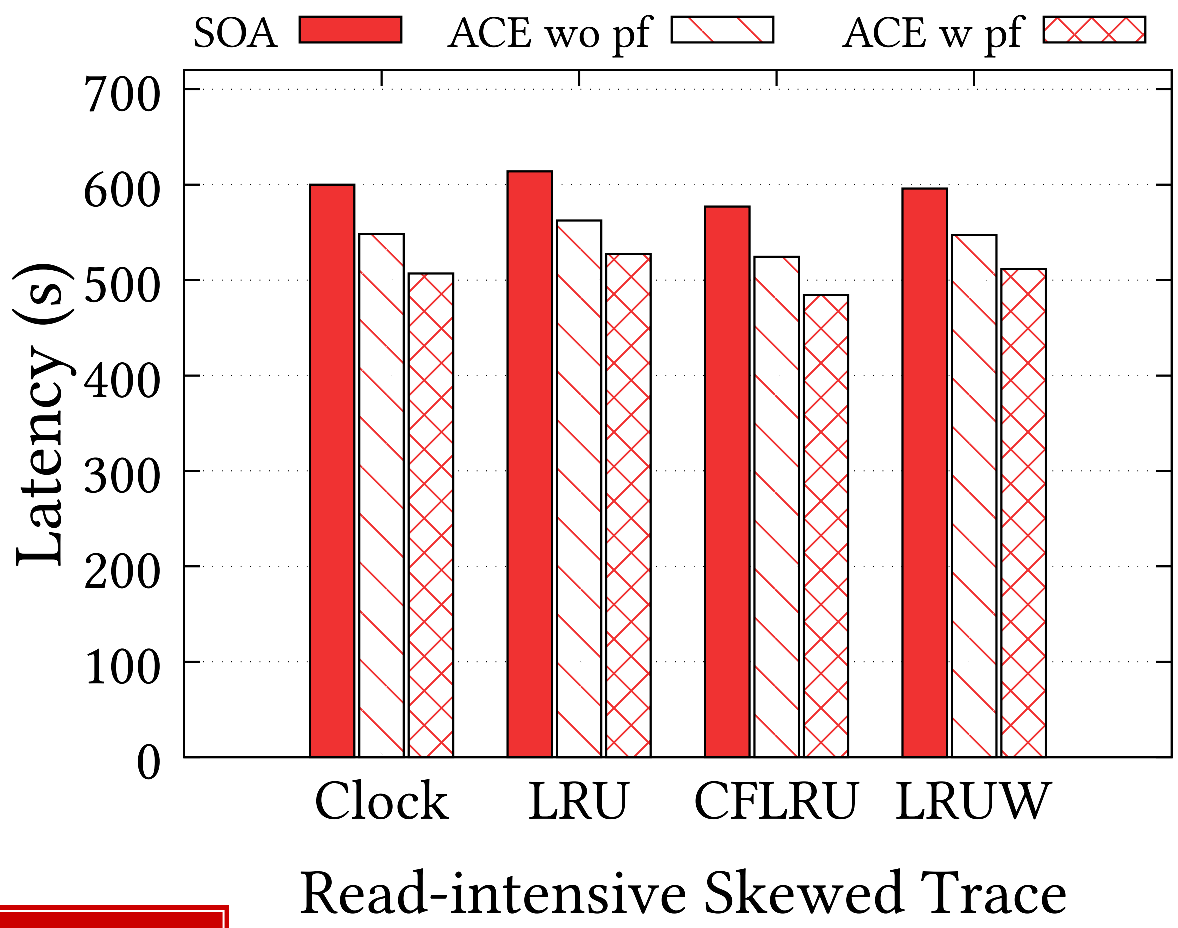
Experimental Evaluation

Device: NVMe SSD

$\alpha = 3, k_w = 8$



Read-intensive workloads also have substantial gain (5-15%)

Benefits comes mostly through prefetching

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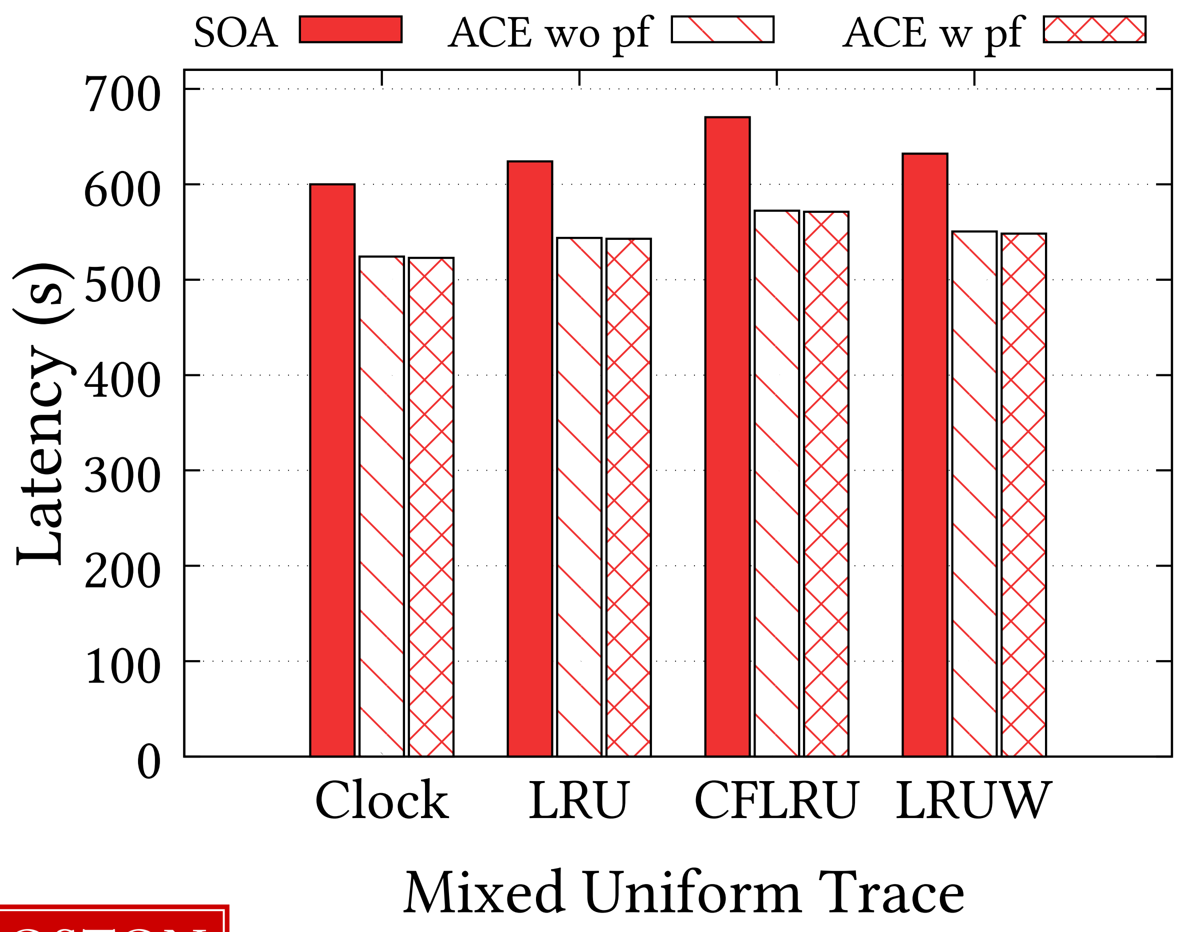
Experimental Evaluation

Device: NVMe SSD

$\alpha = 3, k_w = 8$



The benefits remain significant (~10%) for uniform workloads

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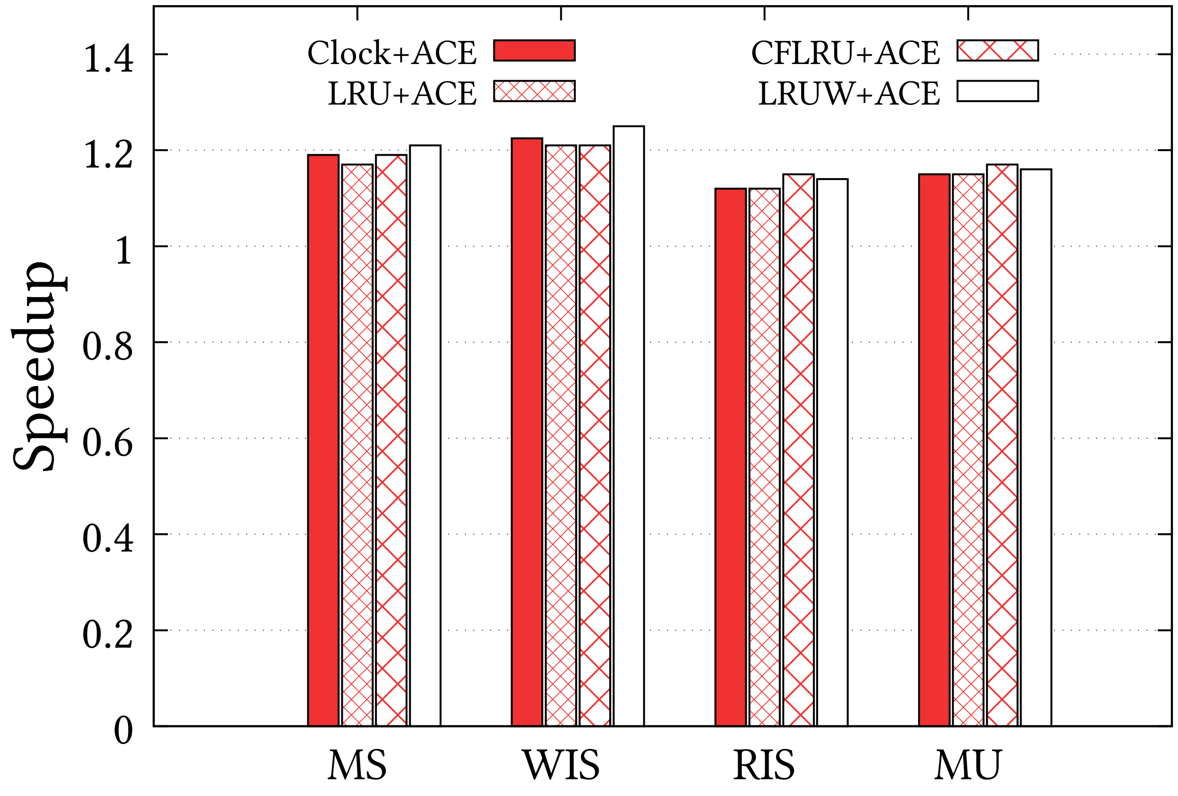
Experimental Evaluation

Device: Regular SSD

$\alpha = 1.5$, $k_w = 8$



Even for devices with asymmetry 1.5, concurrency leads to up to 20% benefit

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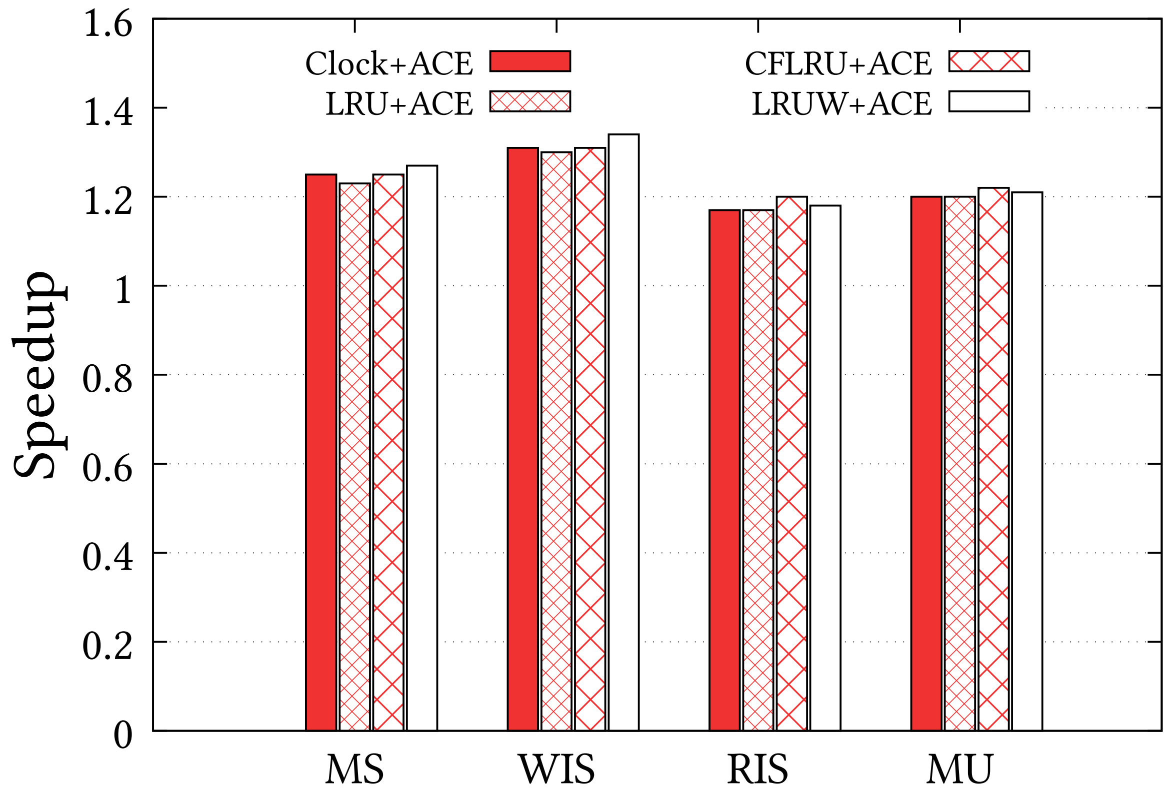
Experimental Evaluation

Device: Virtual SSD

$\alpha = 2, k_w > 19$



The benefits remain for virtual SSDs that we cannot fully benchmark

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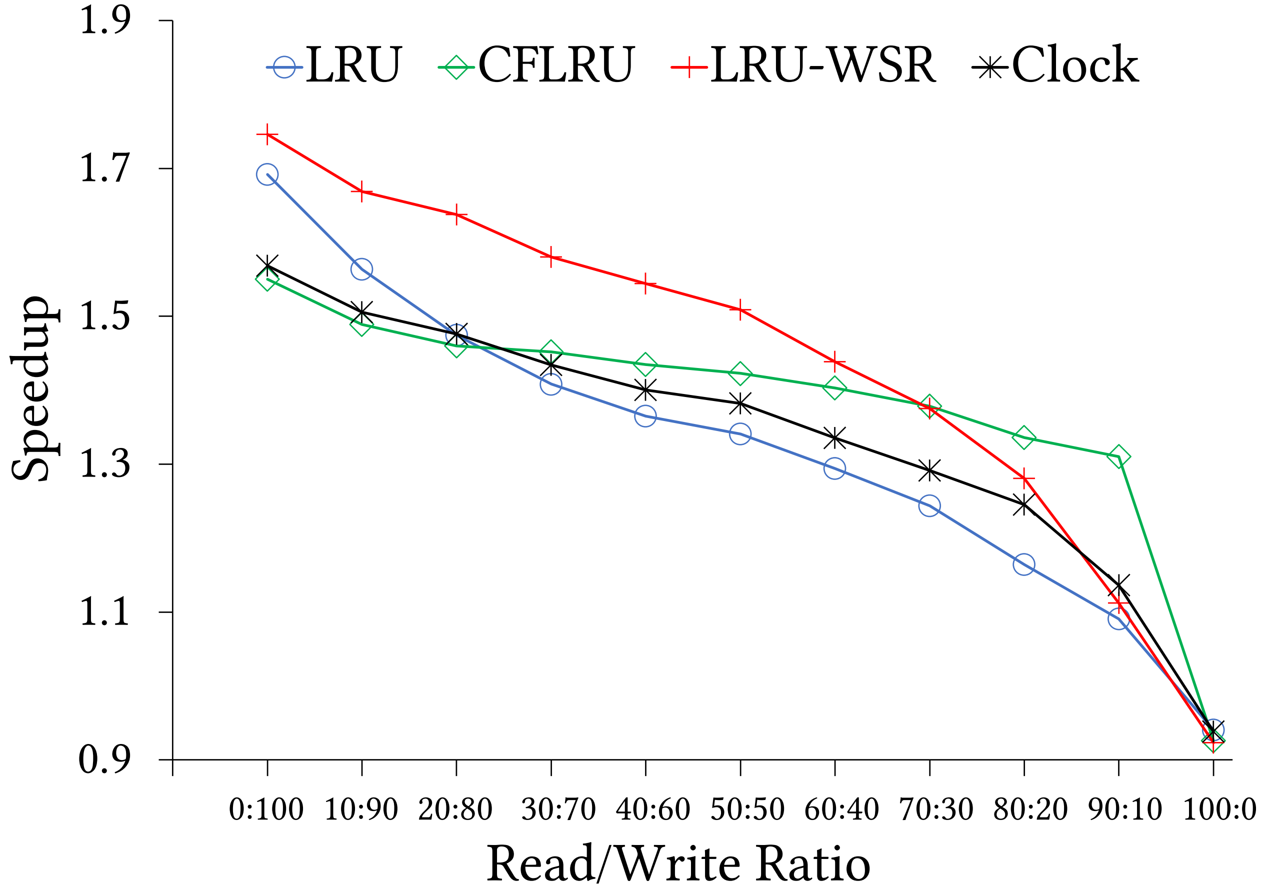
Experimental Evaluation



Device: NVMe SSD

$\alpha = 3, k_w = 8$

For write heavy workloads, gain of ACE can be as high as 1.75x

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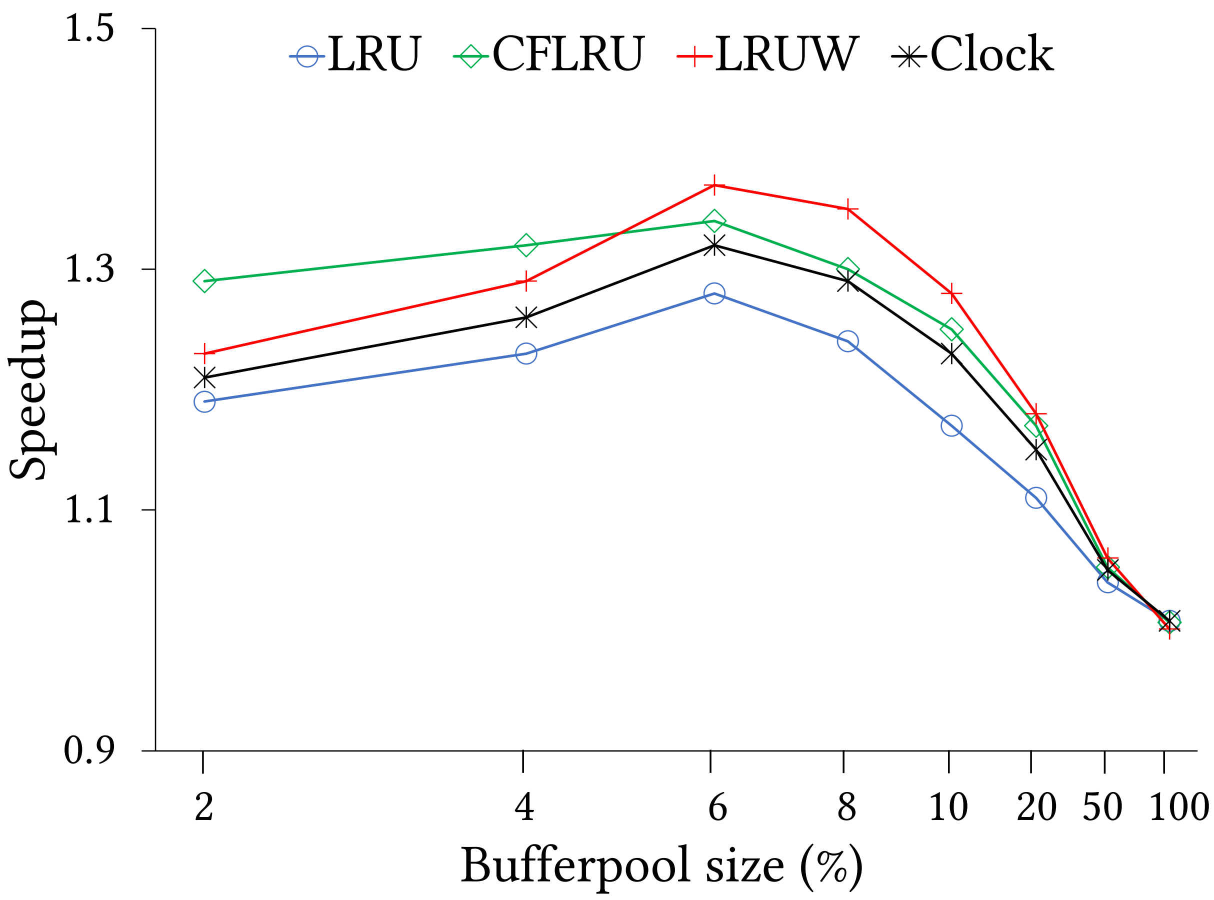
Experimental Evaluation

Device: NVMe SSD

$\alpha = 3$, $k_w = 8$

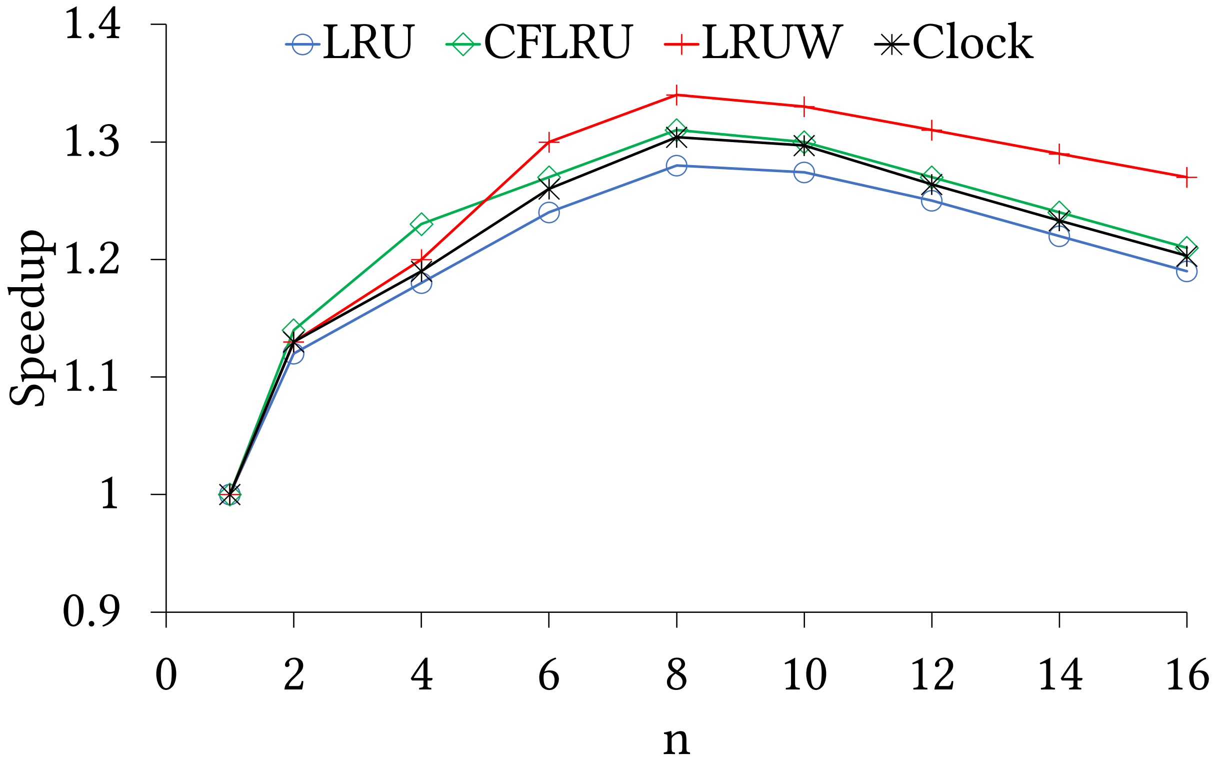


ACE performs particularly well under memory pressure

Experimental Evaluation

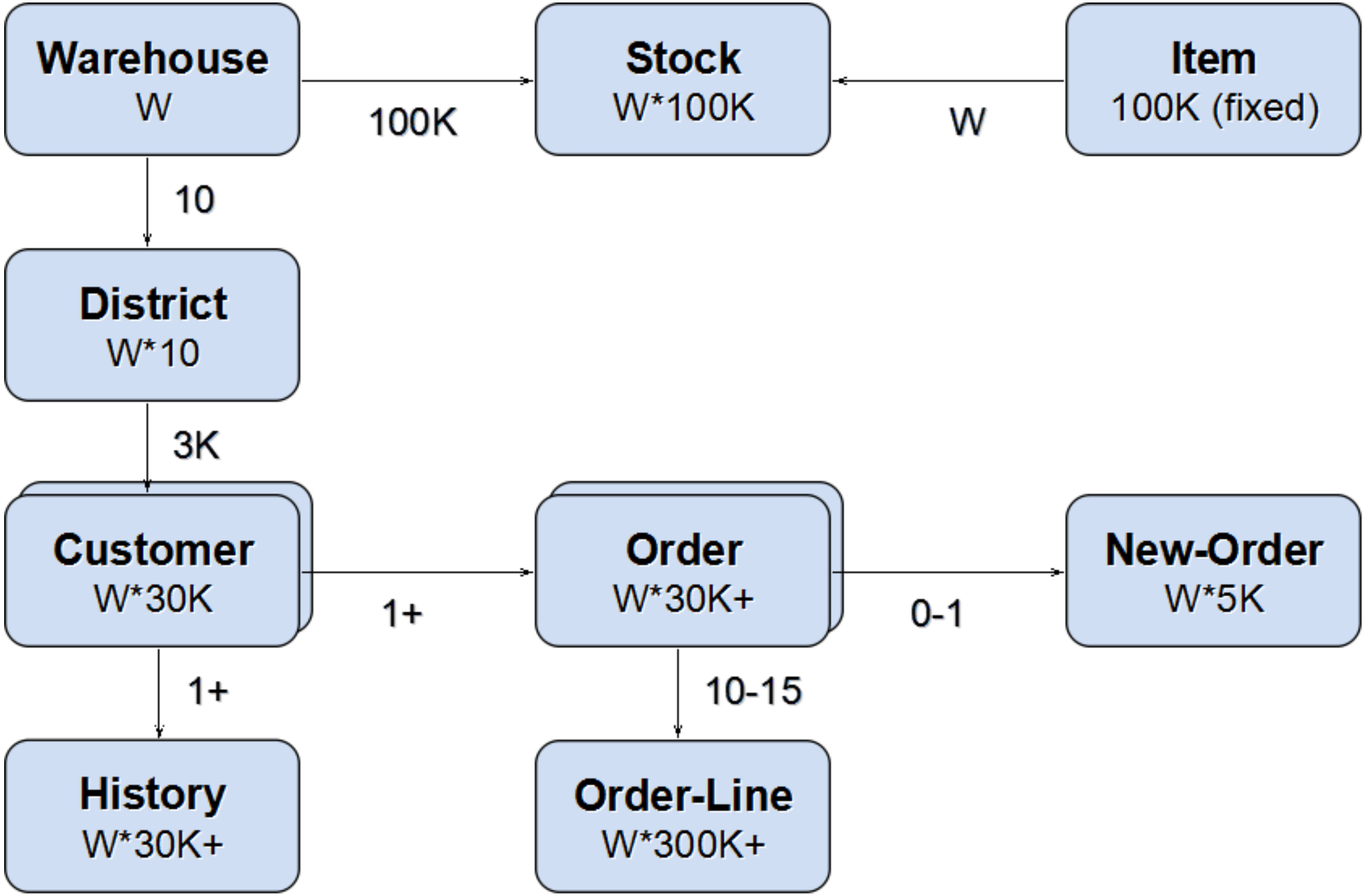
Device: NVMe SSD

$\alpha = 3, k_w = 8$



There is an optimal concurrency for each device.

Experimental Evaluation (TPC-C)



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Experimental Evaluation (TPC-C)

TPC-C consists of 5 transactions

NewOrder (45%)	R/W Mix
Payment (43%)	R/W Mix
OrderStatus (4%)	R-only
StockLevel (4%)	R-only
Delivery (4%)	W-heavy

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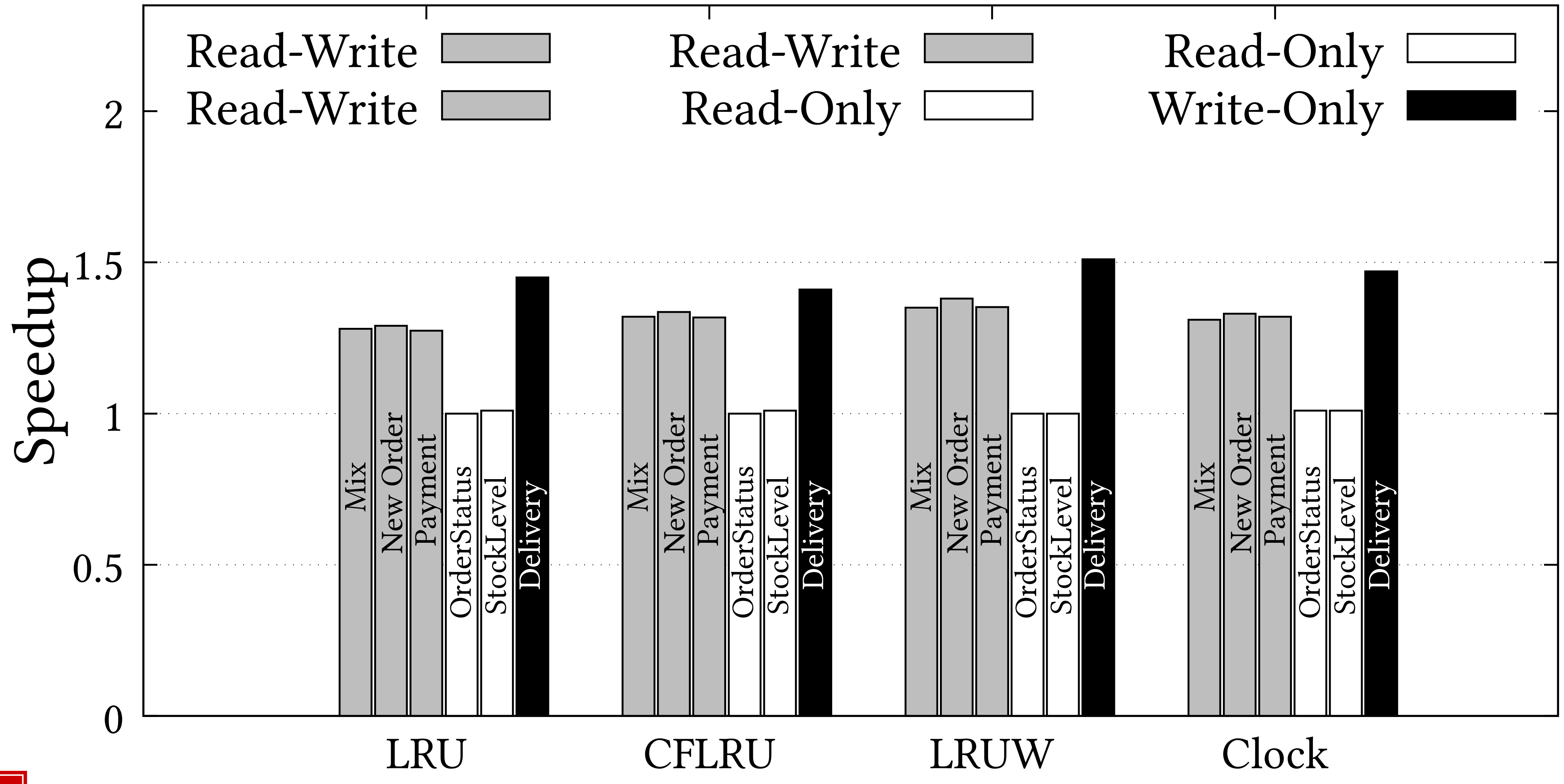
Experimental Evaluation (TPC-C)



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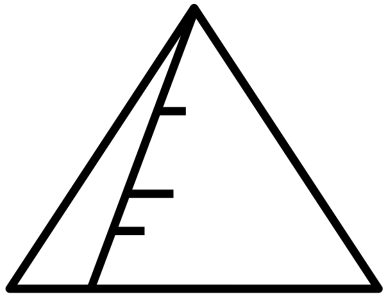
Conclusion

Make *asymmetry and concurrency* part of *algorithm design*

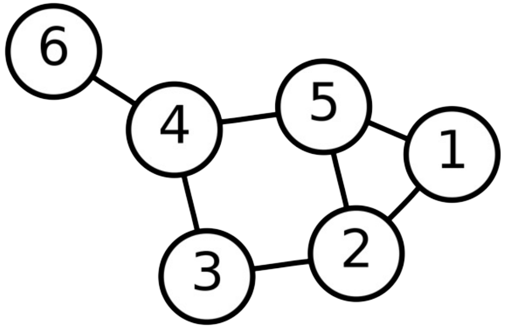
… not simply an engineering optimization

Build algorithms/data structures for storage devices
with asymmetry α and concurrency k

index structures



graph traversal algorithms



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CS 561: Data Systems Architectures

class 18

Asymmetry & Concurrency Aware Storage Management

Prof. Manos Athanassoulis

https://bu-disc.github.io/CS561/